Evaluation of Input Devices for Wearable Computers

Research Thesis for the Degree of Doctor of Philosophy

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Declaration

I declare that:

- this thesis presents work carried out by myself and does not incorporate without acknowledgment any material previously submitted for a degree or diploma in any university;
- to the best of my knowledge it does not contain any materials previously published or written by another person except where due reference is made in the text; and
- all substantive contributions by others to the work presented, including jointly authored publications, is clearly acknowledged.

Joanne Elaine Zucco
Adelaide, May 2015

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Dedicated to…

my nonna, Lina Montarello;
whose life has significantly impacted mine; her faith, character and generosity will resonate in my heart forever

and to

my mum and dad, Marisa and Ned Zucco;
whose love, support and generosity continues to astound and overwhelm me

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Abstract

Effective interaction devices and techniques are essential to the usability of a wearable computer system and can have a significant influence upon its adoption. In light of this, the exploration of wearable human-computer interaction is an important and necessary field of study. However, despite the need to better understand wearable interaction, there has been little work investigating the usability of input devices available in the marketplace suitable for use with wearable computers. Notably, there exists a gap in the literature pertaining to the evaluation of commercial pointing devices suitable for use with wearable computers where participants are evaluated while wearing a computer and a head-worn display (i.e. in a wearable context). This dissertation is positioned within the space of wearable human-computer interaction and presents contributions to the field motivated by the necessity to understand and quantify the commercially available pointing devices suitable for use with wearable computers.

The four pointing devices that have been identified are a handheld trackball, a touchpad, a gyroscopic mouse, and the Twiddler2 mouse. The devices were chosen due to their suitability for use with wearable computers and their documented use in wearable research literature. The devices provide general-purpose interaction (can be used in place of a desk-top mouse) and are representative of the commercial devices available for cursor control and command entry suitable for use with wearable computers. Additionally, the devices are available as commercial, off-the-shelf products.

The body of work presented in this dissertation explores the aforementioned pointing devices via a systematic evaluation over a suite of three different general-purpose tasks (selection, drag and drop and menu selection) and by means of a learnability study (evaluating the devices over an extended period of time). The culmination of the usability studies and synthesis of results provide insights pertaining to the choice and usability of the devices in a wearable context. Specifically, the results derived from the studies presented; provide information to the wearable computing research and industry community regarding the performance of the devices in a wearable context; provide valuable information regarding the usability of the devices that will guide users in selecting a pointing device that is well suited and appropriate for a task(s); and provide a set of metrics by which future wearable devices can be compared against. A set of guidelines and recommendations grounded on experimental and qualitative evidence are

derived from the four usability studies and are intended to be used in order to inform the design of future wearable input devices. In addition to guiding the design process, the guidelines and recommendations may also be used to inform users of wearables by guiding towards the selection of a suitable wearable input device. As an exemplar of the application of the guidelines and recommendations, a pointing device with novel form factor is designed.

Author Publications

The work presented in this dissertation has, in part, appeared in a number of peer-reviewed publications as follows:

- Joanne E. Zucco, Bruce H. Thomas, Karen Grimmer. *'Evaluation of Three Wearable Computer Pointing Devices for Selection Tasks*'. In Ninth International Symposium on Wearable Computers, Osaka, Japan, October 2005. IEEE. (Presented in Chapter 3).

- Joanne E. Zucco, Bruce H. Thomas, Karen Grimmer. *'Evaluation of Four Wearable Computer Pointing Devices for Drag and Drop Tasks when Stationary and Walking*'. In Tenth International Symposium on Wearable Computers, Montreux, Switzerland, October 2006. IEEE. (Presented in Chapter 4).

- Joanne E. Zucco, Bruce H. Thomas, Karen Grimmer-Somers, Andy Cockburn. *'A Comparison of Menu Configurations and Pointing Devices for use with Wearable Computers while Mobile and Stationary*'. In Thirteenth International Symposium on Wearable Computers, Linz, Austria, September 2009. IEEE. (Presented in Chapter 5).

The author has also been involved in work that was **not** a part of this dissertation, listed as follows:

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1

Introduction

1.1 Introduction

Wearable computing has experienced a resurgence, driven by the likes of large influential companies such as Google, Apple, Samsung, Sony and Epson all targeting the mainstream consumer market. Given the relative infancy of mainstream consumer wearable technology, companies are moving to develop their own expressions of wearable computing devices. Innovation in the wearable technology space has produced a variety of devices. Epson has released the Moverio BT-200[1], a binocular head-worn see-through display that is tethered to a small handheld controller (Figure 1). The handheld controller is 120 mm x 55 mm x 19 mm in size and operates the Android platform. Meta is working towards releasing see-through augmented reality 3D binocular eyeglasses called the META Pro[2] (Figure 2). The eyeglasses can be connected to a small pocket computer (Intel i5 CPU, 4GB ram, 128GB SSD, 32hr battery) that comes bundled with the glasses. Meta strives to produce a product that is akin to wearing fashionable sunglasses.



Figure 1: Epson Moverio BT-200[3]

Sony has released the SmartWatch 3[4] and Samsung have also recently released their version of the smart watch called Samsung Gear S[5]. The Moto 360[6] smart watch is

[1] http://www.epson.com/cgi-bin/Store/jsp/Landing/moverio-bt-200-smart-glasses.do
[2] https://www.spaceglasses.com/
[3] http://www.epson.com/cgi-bin/Store/jsp/Product.do?sku=V11H560020
[4] http://www.sonymobile.com/au/products/smartwear/smartwatch-3-swr50/
[5] http://www.samsung.com/au/consumer/mobile-phone/wearables
[6] https://moto360.motorola.com/

produced by Motorola and is one of the first devices to be powered by Android Wear[7] (Google's operating system designed for the wearables market and currently targeting smart watches). Popular and prevalent products under the wearable technology banner are health and fitness trackers such as the Nike+ Fuelband[8], Fitbit Flex[9], and Jawbone UP[10]. Hybrid devices that combine fitness tracking and smart phone notifications in a wristband form factor are also making an appearance on the wearables market, for example: Razer's Nabu[11] and LG's Lifeband Touch[12]. Apple's highly anticipated smart watch called Apple Watch[13] is the company's first contribution to the wearables market. The Apple Watch also includes health and fitness tracking sensors such as an accelerometer to measure body movement and sensors to measure heart rate. Apple Watch marries the functionality of a smart watch, a fitness tracker and a sports watch in one wearable device. Amongst the offerings of wearable devices that are currently or soon to be available is most notably the launch of Google Glass[14], a wearable computer running Android with a monocular optical head-worn display (Figure 3). The computer is built into the arm of Google Glass.



Figure 2: META Pro[15]

In light of the new wave of innovations and form factors specifically designed to appeal to the general public, we will most likely see a boost in the production and mainstream adoption of wearable devices. Juniper Research[16] estimates that the next generation

[7] http://developer.android.com/wear/index.html
[8] http://www.nike.com/us/en_us/c/nikeplus-fuelband
[9] http://www.fitbit.com/au/home
[10] https://jawbone.com/up
[11] http://www.razerzone.com/nabu
[12] http://www.lg.com/au/fitness-and-wearables/lg-FB84-BL
[13] https://www.apple.com/au/watch/
[14] http://www.google.com.au/glass/start/
[15] https://www.spaceglasses.com/products
[16] http://www.juniperresearch.com/viewpressrelease.php?pr=357

wearable devices market (including smart glasses) will be worth in excess of $1.5 billion by 2014, with an estimated 70 million smart wearable units sold in 2017 (compared to $800 million market worth and 15 million sales in 2013).

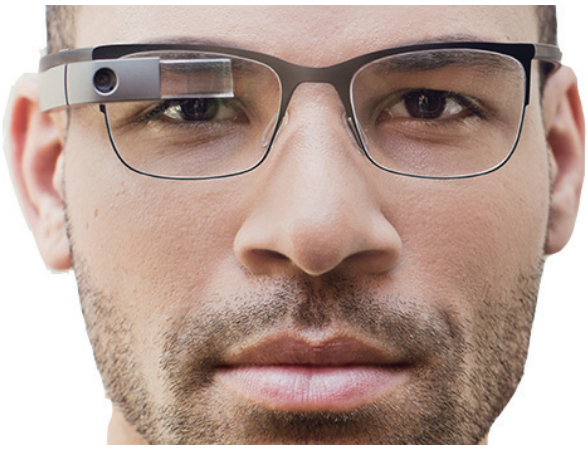


Figure 3: Google Glass[17]

A wearable computer is a small, body worn computer that is worn close to or on the body of the user. As is evident from the above discussion, wearable computing encompasses a wide variety of devices with differing purposes, functions and form factors. Likewise, interaction with the devices is also varied. Interacting with the aforementioned smart watches involves gesturing or selecting on the face of the watch. In addition to gesturing, Samsung Gear S and the Moto 360 also allow voice input for command control and text input. Interaction with Apple Watch is via gesturing on the screen, tapping and pressing on the screen (the device can sense pressure on the face of the watch), via the digital crown situated on the side of the device and by the use of voice input for command control and text input. Interaction with Lifeband Touch involves swiping a finger on the display. Nabu uses simple gestures (e.g. turning one's wrist) for interaction. The Moverio BT-200 head-worn display enables interaction through the use of a touchpad situated on the top of the controller (along with function keys such as home, menu, back, etc.). Interaction with META eyeglasses is via finger and hand gestures performed in mid-air and in front of the body. Users interact with Google Glass using voice commands and a touchpad running along the arm of the device. As an alternative to using voice or gesture to control Google Glass, Google has released MyGlass[18]. My Glass is an application that

[17] https://plus.google.com/+GoogleGlass/photos
[18] http://www.google.com/glass/help/myglass/

allows the user to touch, swipe or tap her mobile phone in order to provide input to Glass. However, researchers have mentioned the possible difficulty of interacting with a touch screen device while wearing a head-worn display [1]. Lucero et al. [2] draw attention to the unsolved problem of the nature of interaction with head-worn displays (i.e. interactive glasses) and highlight the need for research to explore open questions such as, how input is provided to head-worn displays/glasses, and to determine what the appropriate and suitable interaction metaphors are for head-worn displays.

Given the diversity of devices available and that wearable computing is a relatively new discipline, there does not yet exist a standardised way of interacting with a wearable computer, in contrast to desktop computers where a keyboard and mouse are the standard devices. In many cases, however, the requirements for textual data and command entry/control techniques remain the same. Symbolic entry, that is the entering of alphanumeric data, may be performed by keyboards suitable for use in a wearable context (i.e. wrist-worn or hand-held) and via speech recognition (e.g. speech input similar to that available in Google Glass). Command entry/control techniques may be performed via voice commands (e.g. through speech input as utilised in Google Glass) and gestures (e.g. available in Google Glass and Moverio BT-200 by using the touchpad, and in META Pro with finger/hands performed in mid-air and in front of the body). Although these devices are compelling examples of wearable computing, they will typically require the development of specialised software designed to operate specifically for the device and its provided interaction technique(s). The interaction techniques typically provide discrete input that may be directly mapped to a specific action and as a result do not provide general-purpose input. That is, existing applications may not be able to run on these devices easily as the interaction does not necessarily map to the existing software; in which case one will have to re-write or modify the software so that it is suitable for use on the wearable device. Depending upon the software, the mapping of the available input technique to a specific command may not always be possible.

The yet to be released META Pro provides mounting evidence of the ability to create powerful computing devices that are bundled into small, body-worn form factors suitable for mobile computing. In light of this, it is possible to run current desktop applications on a wearable device with the likes of wearable systems (similar to the META Pro), that provide pocket-sized powerful computing power, and display via a socially acceptable

head-worn display/eyeglasses. As a result, there will be a need for general-purpose input such as that provided by means of cursor-control. The prolific use of Graphical User Interfaces found on desktop computers typically requires the use of a pointing device in order to interact with the system. A pointing device such as a desktop computer mouse provides the user with the ability to perform on screen, two-dimensional cursor control. Users who wish to run their desktop applications on their wearable computers [3] will likewise require the use of a suitable pointing device given that the interaction metaphor remains the same. Without the ability to fabricate specialised pointing devices suitable for use with wearable computers, users will therefore need to turn their attention to commercially available input devices. The input devices must be suitable for use with wearable computers and as previously stated, provide general-purpose input. A mechanism for continuous pointing suitable for use with wearable computing is vital [4, 5] as various forms of wearable computing are adopted.

Interest in input devices and interaction techniques suitable for use with head-worn displays is growing, as evidenced by the following investigations that have designed input devices with the intention of being used with a head-worn display; uTrack [4], FingerPad [6], and PACMAN UI [1]. With the release of wearable glasses-based displays that are smaller, less obtrusive and targeted towards the consumer market, research into suitable, subtle and socially acceptable interaction with head-worn displays is crucial. There is growing interest in the necessity to understand appropriate input devices and interaction with head-worn displays (i.e. smart glasses), as evidenced by Lucero et al. [2]; the authors investigate interaction with glasses (utilising the Moverio BT in their study). Serrano et al. [7] explore hand-to-face gestural input as a means of interacting with head-worn displays (utilising the Moverio BT in their studies).

Effective input devices and interaction techniques are essential to the usability of a wearable computing system. With the imminent release of new wearable technology poised to hit mainstream markets, research into wearable input devices and interaction continues to be an important and vital field of investigation. As stated by Thad Starner [8]; "*…when faced with a promising socially significant technology, scientists have a responsibility to examine its potential paths of development and use*".

1.2 Research Questions and Goals

Despite the need to better understand wearable interaction and the availability in the marketplace of pointing devices suitable for use with wearable computers, there is very little published data evaluating these pointing devices. There exists a gap in the literature evaluating commercial pointing devices suitable for use with wearable computers where participants are evaluated while wearing a computer and a head-worn display. Although it may be found that optimal interaction methods for wearable computers may differ from those used in desktop computers, it is important to evaluate the currently available input devices for the following reasons; as a means to empirically determine their effectiveness within a wearable context and inform and guide users of the technology when deciding amongst devices; to provide a basis on which to inform and guide design so that usable and effective input devices irrespective of interaction metaphor can be created; and to derive first hand observations that can provide a comparative basis for novel and innovative input methods and devices emerging from research laboratories. In light of this, the exploration of wearable human-computer interaction is an important and necessary field of study.

A number of commercially available input devices exist that are suitable for use with wearable computers, however, of interest are the devices capable of performing general-purpose interaction via cursor-control. The pointing devices chosen as part of this body of work use different technologies and are therefore representative of the four main interaction methods used to provide cursor-control and command entry. Although there may be a variety of models and form factors available of the devices, they operate in a similar fashion. The four commercially available pointing devices that have been identified are as follows: handheld trackball, touchpad, gyroscopic mouse and Twiddler2 mouse. All four devices enable the user to perform general purpose input (i.e. cursor-control) and can be used in place of a desktop mouse. The devices were chosen due to the following reasons; their suitability for use with wearable computers; their use was noted in the wearable research literature; and they are representative of the commercial devices available for cursor control and command entry. Additionally, the devices provide general-purpose interaction suitable for use with wearable computers and are readily available as commercial, off-the-shelf products.

This research seeks to understand and quantify the aforementioned currently available commercial pointing devices available for use within a wearable context. Of interest are the following questions:

- Whether there is a measurable difference (i.e. effectiveness, efficiency) between the pointing devices in a wearable context.
- Whether a ranking can be established pertaining to the use of the devices in a wearable context.
- Whether certain devices are better suited to certain task(s) and/or mobility condition(s).
- Whether there is an optimal pointing device in terms of operator performance over a suite of tasks and mobility conditions.
- Whether users have a preference of pointing device.

This dissertation seeks to answer the research questions via a systematic evaluation of the pointing devices over a suite of different tasks and a learnability study. The tasks chosen are indicative of typical human-computer interaction within current graphical user interfaces. Of interest are the following:

- Selection usability study.
- Drag and drop usability study.
- Menu selection usability study.

In order to understand the use of the pointing devices over time (learnability study), an extended selection usability study is undertaken. A selection task is chosen for the extended study as selection is fundamental to the above aforementioned suite of tasks. The studies are motivated by the need to address the existing gap in knowledge pertaining to the evaluation of commercial pointing devices suitable for use with wearable computers where participants are evaluated while wearing a computer and a head-worn display.

The work provides valuable insights into the usability of commercially available pointing devices within a wearable context. The studies produce findings that will guide users and designers in selecting a pointing device that is well suited and appropriate for the task(s) for which they are employing the use of a wearable. In addition, the work endeavours to provide insights that will inform the design of future wearable input devices. The body of work seeks to produce findings that will guide the design of wearable pointing devices

while also providing information to the wearable computing research and industry community regarding the performance (i.e. efficiency, effectiveness) and comfort (i.e. satisfaction) of the devices.

1.3 Contributions and Artefacts

The three contributions and artefacts of this body of work are as follows:

- *A systematic formal evaluation consisting of four usability studies designed to understand the commercially available pointing devices suitable for use with a head-worn display and while wearing a computer (i.e. in wearable context).* The four usability studies conducted while wearing a computer and using a head-worn display are as follows:
    - Selection usability study.
    - Drag and drop usability study.
    - Menu selection usability study.
    - Learnability usability study.

  The results of the studies provide information to the wearable computing research and industry community regarding the performance of the devices in a wearable context (i.e. while wearing a computer and using a head-worn display). The results obtained from the studies undertaken provide valuable information regarding the usability of the devices that will guide users in selecting a pointing device that is well suited and appropriate for a task(s) in a wearable context. A set of metrics are derived from the studies which will provide a means for comparisons against future wearable devices. Typically novel devices produced by research laboratories are evaluated against a commercially available device. The comparison is more meaningful if the commercial device has been evaluated within a wearable context and there exists an understanding of the performance and suitability of the device within a wearable context. It may stand to reason that one is comparing the novel device against an unknown quantity if the commercial device has not been evaluated.

- *A set of guidelines and recommendations grounded on experimental and qualitative evidence derived from the four usability studies.* The culmination of the usability studies and synthesis of results provide guidelines and recommendations

that may be use to inform users of wearables by guiding towards the selection of a suitable wearable input device. That is, the guidelines form a checklist that may be utilised as a point of comparison when choosing between different input devices available. In addition, the work also provides guidelines and insights that will be used to inform the design of future wearable input devices.

- *A pointing device with novel form factor for use within a wearable context.* The set of guidelines and recommendations derived from the four usability studies are applied to build a pointing device with a novel form factor suitable for use within a wearable context (i.e. while wearing a computer and for use with a head-worn display).

1.4 Structure of the Dissertation

Chapter 2 presents work relevant to this dissertation, positions this work in the body of existing work and motivates the need for the research. The background chapter opens with a description of wearable computing, presents the ideal or desirable characteristics of a wearable system and provides exemplars of wearable computing. Section 2.3 discusses the input modalities and interaction techniques explored for use with a wearable computer, for example: gesture, speech recognition, pointing. As a result of examining the research literature, it is evident that wearable input and interaction remains a key challenge. How to effectively interact with the information presented via a head-worn display is for the most part an unresolved problem. Researchers have explored different means by which to perform command entry and cursor-control in a wearable system. A mechanism for continuous pointing suitable for use with wearable computing is vital [4, 5]. Novel devices for command entry and cursor-control are presented along with the commercially available pointing devices. Despite the importance of input devices for wearable computing, there has been very little quantitative and qualitative evidence on the usability of such devices [9, 10]. Section 2.4 describes the evaluation methods used in this dissertation in order to ascertain the usability of the pointing devices. Section 2.5 presents the usability studies pertaining to input devices predominantly used for general-purpose interaction in a wearable context, for example: usability studies evaluating point devices, interaction techniques, placement of input devices and longitudinal evaluations. Despite the need to better understand

wearable interaction, there is very little published data evaluating these devices. Section 2.6 highlights the limited number of empirical studies dedicated exclusively to investigating the usability of pointing devices in the marketplace suitable for use with wearable computers. In particular, there exists a gap in the literature evaluating commercial pointing devices suitable for use with wearable computers where participants are evaluated while wearing a computer and a head-worn display; therefore highlighting the importance of exploring wearable human-computer interaction. The chapters that follow Chapter 2 present the results of a formal systematic series of four studies undertaken that evaluate commercially available pointing devices for use with wearable computers. The studies are motivated by the need to address the existing gap in knowledge. The studies are undertaken while wearing a computer and a head-worn display.

Chapter 3 presents the first in the series of studies evaluating the pointing devices performing selection tasks. Target selection was chosen as a starting point given that it is a fundamental interaction operation undertaken in graphical interfaces. The study seeks to understand the pointing devices and their suitability to a generic and fundamental task such as target selection. Selection of targets is performed by positioning the cursor on the target and clicking the select button on the pointing device. Chapter 4 presents the second study that extends the selection study by evaluating four pointing devices when performing an increasingly complex task, that is, drag and drop. Performing a drag and drop operation requires the user to press the button on the pointing device to select the target, move the cursor (while keeping the button pressed) and release the button once the object is repositioned on the destination target. The complexity of the first study is also extended by the introduction of a walking condition in addition to a stationary condition. In Chapter 5, the pointing devices are evaluated performing menu selection tasks. Menu selection is the most common form of command entry on modern computers. The menu structures evaluated in the study consist of two-levels: eight top-level menu items, and sub-menus containing eight menu items for each top-level item. Menu selection was modelled on typical menu interaction found implemented in standard GUI applications. A sub-menu was activated by clicking on its parent item. The target menu item was selected by clicking on the desired item. Menu selection introduces the complexity of the need to employ precise mouse movements required to steer to sub-menu items. The final in the series of studies is a learnability study

presented in Chapter 6 that evaluates how the devices perform given repeated exposure over a series of days. The previous studies predominantly use the measures of task completion time (efficiency), error rate (effectiveness) and questionnaires (satisfaction) as defined in the ISO 9241-9 [11] standard in order to evaluate the usability of the devices. In addition to the attributes of efficiency, errors and satisfaction, Nielsen [12] includes learnability and memorability. This study extends the previous three to evaluate the learnability (by repeated exposure over a series of days) and the retention of skill used to operate the four devices. This study also extends the previous work by deriving dependent measures of throughput and workload for the pointing devices in a wearable context. Throughput is a Fitts' law measure commonly used to evaluate pointing devices or pointing techniques [13, 14]. Throughput is a dependent measure that combines both the speed and accuracy of the movement performance [13, 15]. Throughput measures the rate of information transfer [11] and is measured in bits per second (bps). The larger the value of throughput for a device, the faster it will perform [16]. The subjective measure of workload experienced by a subject when performing a task is obtained using a multi-dimensional scale called the NASA Task Load Index (NASA-TLX) [17]. The overall workload calculation results in a final score between 0 and 100 (0 being light workload and 100 being heavy workload). There have been very few studies that report throughput and workload values for input devices evaluated in a wearable context.

The four pointing device studies undertaken culminate in the production of wearable pointing device guidelines and recommendations, and are presented in Chapter 7. The guidelines and recommendations are derived from the experimental and qualitative feedback collected as a result of the four usability studies. Utilising the guidelines, a pointing device is created with a novel form factor which strives to overcome some of the limitations of the currently available pointing devices. The novel pointing device is also described in Chapter 7. The wearable pointing device is worn on the user's index finger and runs down the back of the user's hand. It is positioned on the hand so as to allow hands-free interaction with the task/environment when the device is not in use. In light of this, the device allows for short grasp/access time as it is designed to be worn continuously attached to the hand. Cursor movement is via an optical mouse sensor and button press is via capacitive buttons. Chapter 8 concludes the dissertation and presents future work.

2

Background

2.1 Introduction

This chapter presents previous work relevant to this dissertation. The chapter begins with a description of a wearable computer, presents the ideal or desirable characteristics of a wearable system, and provides exemplars of wearable computers, past and present. Following this is a discussion pertaining to the input modalities explored for use with wearable computing. Although interacting with a wearable computer poses challenges not relevant to its desktop counterpart, the requirements to enter textual data and control the wearable in the way of command entry remain the same. Researchers and users of wearable systems have explored different means by which to perform command entry and general-purpose interaction in a wearable system. Of particular interest are the pointing devices that are available for general-purpose interaction and that are suitable for use with wearable computers. An exploration of pointing devices presented in research literature and available commercially for use with wearable computers follows the discussion of input modalities. This chapter then presents a description of the evaluation methods typically used in order to evaluate the usability of pointing devices. Despite the need to better understand wearable interaction, there have been a limited number of empirical studies investigating the usability of pointing devices for wearable computers. This chapter concludes by describing the relevant usability studies presented in literature pertaining to the evaluation of wearable input devices.

2.2 What is a Wearable Computer?

A wearable computer is a small, body worn computer that is worn close to or on the body of the user. The term Wearable Computer encompasses a wide variety of devices that differ in form and function. Wearable computers have typically been defined by describing their desirable or ideal characteristics [18, 19] instead of specific hardware or software configurations and requirements. For example, Rhodes [20] defines wearable computers as having the following characteristics; being portable while in use, enabling hands-free or hands-limited use, having the ability to sense the user's environment, communicating information even when not in use, and being always on. Mann [21-23] describes a wearable computer as "a computer that is subsumed into the personal space of the user, controlled by the user, and has both operational and interactional constancy, i.e. is always

on and always accessible". Mann [24] describes three modes of operation being constancy (always ready), augmentation (augmenting the intellect or senses) and mediation (block, filter or modify information being exchanged). In addition to the three modes of operation, Mann also describes the following attributes [24] and properties [22, 23]; unrestrictive (facilitates the engagement in other activities while using it, i.e. it is not the primary task), not monopolizing the user's attention, observable (it can get your attention as the output is visible at all times), controllable by the user, attentive to the environment, used as a communication tool (allowing for expressive interaction), constant (always on and ready) and personal (it feels like it is a part of or a natural extension of the wearer and others cannot observe or control it without your permission). Starner [19, 25] describes the ideal attributes of wearable computers as having the ability to:

- "Persist and enable constant access to information" [19, 25] – a mobile and physically unobtrusive device enabling seamless interaction between the user and the wearable, when necessary, as appropriate and with little effort.
- Sense and model the user's environment, the user's physical and mental state in addition to its own state [19, 25].
- "Adapt its input and output modalities" [19, 25] based on the user's context i.e. apply those that are most appropriate and socially apt depending upon the setting and situation.
- "Augment and mediate interactions with the user's environment" [19] – the ability to gather information, filter it and present it based on the user's needs and preferences. The wearable should manage potential interruptions such as emails or phone calls appropriately.

Researchers have cast an exciting vision of wearable computing, however, we have not yet achieved the 'ultimate wearable computer' [26]. The following section provides exemplars of past and present wearable systems.

2.2.1 Examples of Wearable Systems

The first wearable computer was designed and implemented by Edward Thorp and Claude Shannon [27] in 1961 to predict the game of roulette and consisted of a cigarette pack sized computer, two micro-switches placed in shoes and a small in ear speaker. The micro-switches (operated by the big toes) were used to initialize the computer and to provide ball and rotor timing information to the computer. A musical scale consisting of

eight tones was used in order to map each tone to a corresponding octant. The tone communicated via the small in ear speaker indicated the octant upon which to place the bet. Although technically wearable, the device was task specific and purpose-built specially to predict roulette outcomes.

Researchers at Carnegie Mellon University developed the VuMan series of wearable computers. Although also application specific in nature, these systems more closely resembled the architecture of desktop computers although differed in their form factor and in their use of novel input devices. The VuMan 1 [28] developed in 1991 was used to navigate through electronic construction blueprints. The VuMan 1 consisted of a small wearable computer weighing less than one kilogram (with an adjustable strap for wearing on the shoulder or across the chest), a three-button input device and the Private Eye head-worn monocular display. The centre button of the input device was used to select icons at the bottom of the screen while the outer two buttons were used to select the functionality within the selected icon. Interaction consisted of scrolling up, down, left and right and the ability to zoom in and out.

The VuMan 2 [29] developed in 1992 was mainly used as a CMU campus tour navigation assistant although maintenance and repair, security and fire fighting and assembly operation applications were also available by inserting different flash memory cards. The form factor was similar to the VuMan 1 however was designed to provide more functionality while being simpler, smaller, lighter and consuming less power. Using the menu-driven user interface, the user could locate a person or building on campus and find and display information about a person or campus amenities. Interaction with the system was via a three-button mouse which allowed the user to select items (the buttons mapping to different screen dependent commands) and move an on-screen cursor. The input device was designed to be held in the hand or mounted on the user's body.

In 1994, a further iteration of the VuMan series was developed and called the VuMan 3 [30]. VuMan 3 was used to support maintenance tasks providing the ability to display and interact with reference manuals. This iteration introduced a rotary dial input device (with selection buttons situated around the dial) [31] that was embedded in the housing of the computer. The computer was attached to a belt and worn on the hip. The dial drove the design of the interface. Menu/list items were selected by turning the dial (in either direction) and selecting via the buttons surrounding the dial [31, 32]. Both the VuMan 2

and 3 used the Private Eye head-worn display as used in VuMan 1. In 1996, a descendent of the VuMan 3 [31] was designed with multiple possible input devices in order to support different applications – a dial and a circular touchpad to be used when the dial was not appropriate.

Interspersed in the VuMan embedded systems series of wearable computers was the Navigator 1 and 2 [33] general-purpose machines developed in 1993 and 1995 respectively. The Navigator 1 ran a new Campus Tour application using off-the-shelf interface components [33] and was worn in the small of the back. Users interacted with the system using speech and a commercially available handheld trackball [31] in order to position an on-screen cursor. The Navigator 2 ran a custom aircraft inspection application allowing users to interact with the system via speech and a pressure sensitive joystick. The Navigator 2 was worn on the hip. The successor to these systems was the Spot general-purpose wearable computer, released in 2002 [34].

There have also been other more general-purpose systems that have been designed and implemented by the research community and commercially. A wearable computer developed by Thad Starner [8] in 1993 and named the "Lizzy" in 1996 was developed for general purpose, everyday use. The Lizzy consisted of a PC/104 based computer (running the Linux operating system), Private Eye display for output and a Twiddler one-handed keyboard for input. The computer was designed to be carried in a shoulder satchel, backpack, waist-pack or vest. In 1997 the specifications and instructions for building the Lizzy wearable computer were released to the public. The Lizzy or variations of it have been used for a number of wearable computing applications, for example; wearable video camera [35] designed to capture events on behalf of the user, wearable remembrance agent [20, 36] designed as a memory aid to bring to mind (via the display) context relevant information to the user, and the sensing of wearers affective patterns [37] such as mood, heart rate, respiration etc.

The Chi-3 (x^3) [38] developed at the University of Birmingham consisted of a PC/104 based computer (running the Windows 95 operating system) in a custom made case, Garmin GPS (tracking), MicroOptical head-worn display and a trackball mouse. The system was housed in a shoulder strap worn across the body. A prototype application to support evidence recovery at a crime scene used the Chi-3 [39] platform. QBIC [40] is an

example of a general-purpose wearable computer with a small form factor that is housed in a belt buckle and worn on a belt.

Wearable computer systems have also been constructed by utilising off-the-shelf commercially available hardware in the form of a laptop and other necessary instruments mounted on a backpack of sorts. The touring machine [41] was made up of a Fieldworks 7600 laptop (133MHz Pentium, 512K cache, 3 ISA and 3 PCI cards, 64 megabyte RAM, 2 gigabyte disk), Omnicomp 3Demon graphics card, Virtual I/O i-glasses see-through head-worn display (with built-in orientation tracking), Trimble DSM GPS receiver for position tracking, radio modem, and a NRG Power-MAX NiCad rechargeable battery belt. The user also held a handheld computer and stylus (a touchpad was mounted on the back of the handheld and was used to select menu items displayed via the head-worn display). The Windows operating system was used on both devices. The touring machine was the first outdoor augmented reality system and was used to overlay textual information about Columbia University's campus via the head-worn display and further information via a handheld computer. Using a similar, updated wearable system, the campus tour guide work [41] was built upon by Höllerer et al. [42] to display multimedia presentations pertaining to campus events and 3D visualisations of buildings that once existed.

The Tinmith mobile augmented reality platform was originally used to assist with outdoor navigation and visualisation of virtual information [43, 44] via a see through head-worn display. Tinmith-Metro [45] was an extension of this work and enabled the modelling of large outdoor structures (e.g. buildings) and the placement and manipulation of pre-existing objects such as street lights, rubbish bins and benches in the environment. The wearable computer system consisted of a Gateway Solo P2-450 laptop, an intersense IS-300 tracker (orientation tracking), Garmin 12XL GPS with DGPS (position tracking) and Sony Glasstron PLM-700e display. The user interacted with the system using Tinmith-Hand [46], a novel user interface using vision tracked pinch gloves that provided a tracked 3D cursor for selection and manipulation and a menu system for entering commands. The wearable computer system evolved from being mounted on a backpack of sorts [47] to being housed in a custom made case which was attached to a belt and positioned in the small of the back. The Tinmith system has been used by the ARQuake [48] application (augmented reality version of the desktop first person shooter game named Quake) and

to communicate situational and navigational information using 'god-like interaction' [49] in order to facilitate collaboration between outdoor and indoor users.

The Battlefield Augmented Reality System (BARS) [50] consisted of a wearable computer (Dell Inspiron 7000 Notebook), Sony Glasstron LDI-D100B see-through head-worn display, InterSense InertiaCube2 (orientation tracking), Ashtech GG24-Surveyor (position tracking), Wavelan wireless network card and a FreeWave Radio Modem. Users interacted with the system using a wrist-mounted keyboard and a wireless hand-held gyroscopic mouse. The system was designed to explore mobile augmented reality and assist with situational awareness for military operations in urban terrain. Baillot et al. [51] used the BARS platform to create 3D models of urban environments.

Researchers have also explored garment integrated wearables in order to make them as inconspicuous as possible. The e-SUIT [52] is an example of a wearable computer embedded into a business suit. The wearable system consists of an iPAQ PDA placed in the suit pocket and a Matsucom wrist watch computer. A pager motor attached to the shoulder of the jacket and three LEDs sewn into the cuff of the suit jacket provide output. Input is provided via capacitive buttons located inside of the suit jacket. The e-SUIT is used to interact with Microsoft Pocket Outlook. The shopping jacket [53] utilises a sports blazer to house the computer and devices. The wearer uses speech to provide command input and output is via an earpiece or hand-held display. The jacket was used to alert the wearer to shops stocking items of interest, display a list of goods available along with comparative prices and direct the wearer to appropriate shop locations. The CyberJacket [54] ran a tourist guide application that varied the way output was presented in order to suit the wearer's activity. MIThril [55] was integrated into a vest design and used as a research platform into context aware and general-purpose wearable applications [56]. The wearARM [57] is another platform that was designed to easily assimilate into clothing and was also incorporated in the MIThril system [58].

A number of commercial general-purpose wearable computers have appeared on the consumer market. Companies such as Xybernaut, CharmIT and ViA have released wearable computers that were bundled with Operating Systems such as Microsoft or Linux. Commercially available general-purpose wearable computers have been met with limited mainstream consumer success (perhaps due to their ungainly appearance), however they have typically been adopted by industry for industry based applications

(where conspicuous systems and devices are less likely to be out of place), used by the military and used as a tool to further wearable research. In a recent study however, Baumann et al. [59] encountered a reluctance by workers in an automobile company to participate in their study due to the appearance of the wearable hardware.

A wide range of devices that differ in form and function fall under the wearable computer banner. Eurotech[19] currently has the Zypad BR2000 (Windows 7 or Wind River Linux) body worn and Zypad WL1500 (Windows CE) wrist worn wearable computers available on the market. The smart phone is the most widely adopted wearable computing device available today. The smart phone places computational and graphics power in the pockets [26] and handbags of the population in a form factor that is socially acceptable to carry and to interact with. Wearable systems are able to make use of the smart phone as a computational device. Other wearable devices embed the computational component in the device itself, exemplars of this are described in the remainder of the paragraph. Google Glass[20] is a wearable computer running Android with a monocular optical head-worn display. Users interact with Google Glass via voice commands and a touchpad running along the arm of the device. The M100 by Vuzix[21] is another example of a monocular head-worn display running the Android OS. Voice commands offer hands-free interaction and the device includes button controls that are integrated along the top of the device. Motorola offers the HC1[22] headset computer (Microsoft Windows CE 6.0 Pro), which responds to voice commands or head tilt gestures for application command and control. The Moverio BT-200[23] is a binocular head-worn see-through display running Android and is tethered to a handheld controller enabling interaction via a trackpad situated on the controller.

The smart watch is another example of the computational component embedded in the device and worn on the wrist. Examples of smart watches include IBM's Linux watch [60] along with more recent versions such as Sony's SmartWatch 3[24], Samsung's Gear S[25], i'm

[19] http://www.zypad.com/zypad/products/
[20] http://www.google.com.au/glass/start/
[21] http://www.vuzix.com/consumer/products_m100/
[22] http://www.motorolasolutions.com/US-EN/Business+Product+and+Services/Mobile+Computers/Wearable+Computers/HC1
[23] http://www.epson.com/cgi-bin/Store/jsp/Landing/moverio-bt-200-smart-glasses.do
[24] http://www.sonymobile.com/au/products/smartwear/smartwatch-3-swr50/
[25] http://www.samsung.com/au/consumer/mobile-phone/wearables

Watch[26], and Pebble / Pebble Steel Watch[27]. Google have unveiled Android Wear[28], an operating system designed for the wearables market. Android Wear's current target is the smart watch platform. The Moto 360[29] by Motorola is one of the first devices to be powered by Android Wear and following suit, Sony's SmartWatch 3. Health and fitness trackers are another form of wearable technology containing sensors to report the physical state and performance metrics of the wearer, for example: Nike+ Fuelband[30], Fitbit Flex[31], Jawbone UP[32] and BodyMedia FIT[33]. Razer's Nabu[34] and LG's Lifeband Touch[35] are hybrid devices that combine fitness tracking and smart phone notifications in a smart wristband. Interaction with Lifeband Touch is via swiping a finger on the display. Nabu uses simple gestures (i.e. turning your wrist) for interaction. Nabu has two screens, a public display (same position as a watch face) and a private display (positioned on the underside of the wrist). Apple's highly anticipated and soon to be released smart watch called Apple Watch[36] is Apple's first contribution to the wearables market. The Apple Watch also includes health and fitness tracking sensors such as an accelerometer to measure body movement and sensors to measure heart rate. Apple Watch marries the functionality of a smart watch, a fitness tracker and a sports watch in one device. Interaction with Apple Watch is via gesturing on the screen, tapping and pressing on the screen, via the digital crown situated on the side of the device and via voice input for command control and text input. Recon Jet[37] houses the computational component in a monocular display that is mounted on sports glasses. The device has third party sensor and smart phone connectivity. The Recon Jet is currently targeted at athletes and displays performance metrics. Out of the box, users interact with Recon Jet using an optical touchpad that is situated on the device.

As explored in the preceding discussion, wearable computers encompass a wide variety of devices with differing functions, form factors and modes of interaction.

[26] http://www.imsmart.com/en
[27] https://getpebble.com/
[28] http://developer.android.com/wear/index.html
[29] https://moto360.motorola.com/
[30] http://www.nike.com/us/en_us/c/nikeplus-fuelband
[31] http://www.fitbit.com/au/home
[32] https://jawbone.com/up
[33] http://www.bodymedia.com/
[34] http://www.razerzone.com/nabu
[35] http://www.lg.com/us/fitness-activity-trackers/lg-FB84-BM-activity-tracker
[36] https://www.apple.com/au/watch/
[37] http://www.reconinstruments.com/products/jet/

2.3 Input Modalities for Wearable Computers

Input modalities and interaction techniques suitable for wearable computers are well researched areas, despite this, how to seamlessly and appropriately interact with a wearable computer is still a challenging, multifaceted problem that requires attention. Appropriately and effectively interacting with a wearable was a well documented issue and challenge at the advent of wearable computers and although much research has been undertaken in this area, for the most part, it remains as an unsolved problem that is vital to wearable computing. The importance and challenge of designing and creating suitable interfaces for wearable computing has been well noted throughout the literature [4, 19, 61, 62]. The pending introduction of new wearable technologies may change the landscape and bring with it new challenges or further highlight the existing ones as we seek to resolve the existing wearable interaction questions.

Although researchers have made significant advancements in the many aspects of wearable computing [26], input techniques continue to be a key challenge [4]. Interacting in a wearable context brings with it challenges such as; appropriateness of interaction modality or technique, having to divide attention between interacting with the wearable and performing a simultaneous or primary task [63], the practicalities of device size, weight and unobtrusiveness [61, 64], suitable access time [65, 66] and the social consequences and implications of doing so [67, 68]. Although the general heuristic is for interfaces that do not monopolise the user's attention [24], i.e. minimum attention interfaces [63], the range of applications possible on a wearable computer means that there will naturally be a broad spectrum of attention requirements [61], for example: certain augmented-reality applications will typically require more of the user's attention than simply checking the weather; composing an email will take more of the user's attention than glancing at the time, etc. Although interacting with a wearable computer poses challenges not relevant to its desktop counterpart, the requirements to enter textual data and control the wearable in the way of command entry remain the same. With desktop systems, this is typically performed by the keyboard and mouse respectively. Given that users are typically mobile (whether walking or standing, etc) when interacting with a wearable computer, the use of traditional input devices are therefore not suitable as they are large and bulky and require a flat, level surface on which to operate. The challenge is to find suitable input modalities and interaction

techniques for wearable computers. The primary task being undertaken by a user while interacting with the wearable computer adds further complexity as one or both hands may be occupied while the user is performing the task, the attention requirements may vary greatly and the task or user's context may exclude particular forms of input.

Thad Starner [61] states that "Wearable peripheral designers must consider trade-offs between usability, portability, and unobtrusiveness for every device they make." Rekimoto [64] recommends that input devices for wearable computers enable hands-free operation or the ability to quickly change between holding the device and putting it away, and be as natural and unobtrusive as possible. In order to be appropriate for everyday use [64], input devices should have a form factor that is socially acceptable, comfortable and designed to be worn for a long-time. Ideally, the user should be able to expend little to no visual attention in order to access and use a manual interface [69].

Appropriate input modalities are fundamental to wearable interaction. Research in the field has explored hands-free input such as gesture and speech recognition [70-73]. Starner et al. [74] developed an infrared vision system in the form of a pendant in order to detect hand gestures performed in front of the body and used to control home automation systems. SixthSense [75, 76] uses a camera and projector that can be either attached to a hat or combined in a pendant and worn on the body. The system tracks the user's index fingers and thumb (using coloured markers) enabling in-air hand gestures. GestureWrist [64] is a wrist worn device that recognizes hand gestures by measuring arm shape changes and forearm movements. Other researchers have also explored the use of wrist worn interfaces [77-80] that recognise hand gestures. GesturePad [64] is a module that can be attached to the inside of clothes allowing gesturing on the outside of the garment of clothing. PocketTouch [81] allows through garment, eyes-free gesture control and text input. Hambone [82] is a bio-acoustic gesture interface that uses sensors placed on either side of the wrist. Sound information from hand movements is transmitted via bone conduction allowing the mapping of gestures to control an application. Skinput [83], OmniTouch [84], SenSkin [85] and Weigel et al. [86] explore using the skin as an input surface. Serrano et al. [7] explores the use of hand-to-face gestural input as a means to interact with head-worn displays. Glove based systems [46, 87-90] are also used in an endeavour to enable hands-free interaction in that the user is not required to hold a physical device. Researchers have also explored textile interfaces where

electronics are integrated/woven into the fabric of garments for wearable interaction, for example: Pinstripe [91], embroidered jog wheel [92]. An emphasis of the wearable research community has also been to explore implicit means of obtaining input such as context awareness [93-95] and activity recognition [96-100].

Although advantageous in that the above modalities facilitate hands-free or hands-limited interaction with a wearable computer, they are not without their own individual limitations. The typically imprecise nature [101] of speech recognition software has the potential to frustrate users and impede interaction. Factors such as language abilities [9, 102, 103], changes in voice tone due to stress or surrounding noise levels [104, 105] and environmental demands such as being too windy or background noise affect voice recognition levels [73, 106]. Speech recognition was omitted from a comparative study conducted by Chamberlain and Kalawsky [10] as a pilot study revealed it to be problematic. Shneiderman [107] states that speech has its limitations when used for human-computer interaction and interferes with cognitive tasks, such as problem solving and memory recall. There are also privacy issues surrounding the speaking of information and social implications to vocalising commands [71]. It may not be suitable or socially acceptable to vocalise a command, for example, while in a meeting, taking a lift or in a movie theatre. More simply put, people seek appropriately quiet rooms [107] and privacy. Likewise, social context and social acceptability [108] must be taken into consideration when gesturing [109-111]. The wearer may not feel comfortable gesturing in public. Large or awkward gestures may not be socially acceptable or appropriate and may ostracise or unnecessarily draw attention to the user. However, subtle gestures may falsely trigger (or accidentally) as a result of the user's normal movement [112]. Even though gesturing is classified as hands-free interaction, typically one or both hands are occupied while performing the gesture and cannot be engaged with the task. Mid-air gesturing may be prone to fatigue [113]. Although the user is also not required to hold a physical device with glove based systems, having extra material surround the hand may hinder the task, for example: reduce tactile feeling, or interfere with reaching into tight spaces. Glove based systems may also interfere with ordinary social interaction [64], for example shaking hands, etc. While textile interfaces provide controls that are always with the wearer, they may suffer from accidental touches or bumps that unintentionally activate a command [69, 114]. The ability to quickly access controls without expending too much visual attention and the appropriate placement of controls in a socially

acceptable, gender neutral and fashionable manner are important challenges in the design of textile interfaces [69, 114].

Several researchers [63, 115, 116] have also noted that the desktop metaphor (WIMP – Window, Icon, Menu, Pointer) is not suitable for use with wearable computers. The concerns pertain to the attention demands placed on the user and the fine motor control required to interact with the system. However, similar may also be said about interacting with a smart phone. Although the widely adopted smart phone is a powerful computational device that has a socially acceptable form factor [117], for the most part, interaction with the device typically requires the user's full attention whereby the eyes are required to focus on the screen of the device for interaction. Research has shown that interacting with mobile devices when walking is difficult [118-120], it identifies the demand placed on attention resources as a result of having to attend to the device and continually sample the environment [121] while mobile and also describes the challenge of holding an additional object, for example, bag, pen, etc. [122-124]. The eyes occupied, heads down nature of the mobile phone forces users to retreat from observing the world around them rather than being attentive to it [66]. Researchers [125] have also shown that users of mobile phones while walking experience reduced situational awareness, distracted attention and unsafe behaviour. Distraction while walking as a result of interacting with a mobile phone increases the risk of having an accident or causing injury [125]. Using a head-worn (monocular or binocular) display teamed with a smart phone is one possible way forward in that it offers a head-up interface allowing the user to more easily pay attention to the world around them [66], however, this brings to light new challenges of how to appropriately interact with and provide input to interactive glasses / head-worn displays [1, 2, 126]. There is a need for suitable interaction interfaces to be used with head-worn displays [1]. Limited work has been undertaken pertaining to low-attention interfaces for users of head-worn displays [61]. Google have released MyGlass[38] which provides an alternative to using voice or gesture to interact with Glass. My Glass allows the user to touch, swipe or tap her mobile phone in order to provide input to Glass as another means to control the device. Whilst the use of a smart phone is advantageous for those individuals who do not feel comfortable with or find themselves in settings where using voice commands or gesturing may be inappropriate, the phone

[38] http://www.google.com/glass/help/myglass/

itself will occupy either one or both of the user's hands. The smart phone when used as an interaction/input device as described above, does not have a suitable, comfortable ergonomic form factor that one would expect of a wearable input device. In addition, researchers have highlighted the difficulty with using a touch screen while wearing a head-worn display [1]. Typically, interaction with a smart phone requires that either one or both hands be occupied [127]. In addition, smart phones lack immediacy [66] in that they are typically kept in a pocket, on a belt clip or in a bag and it takes time to access the device and have it ready for use [65]. It also takes time to put the device away when no longer needed. Devices should be easily and quickly accessible [65].

A study in mobile interaction undertaken by Oulasvirta et al. [121] found that the continuous attention paid to a mobile device happened in bursts of four to eight seconds due to the necessity of the user to switch between the mobile device and negotiating the environment. Ashbrook [128] builds on this work to suggest that interactions with a device should take less than four seconds to complete (called microinteractions). Constraining interactions to under four seconds enables the user to minimize the disruption to the task being performed [128], minimize the amount of attention devoted to the interaction [66] and facilitates quick and natural interactions [66]. A study performed by Ashbrook et al. [65] explored the time taken to get a device ready for use (i.e. access an interface). The authors found that a device placed on the wrist was accessed faster than the same device when placed in a pocket or holster [65]. Wrist based interfaces have been explored by researchers, for example, Facet [129], WatchIt [130]. Although wrist based interfaces provide a way of facilitating fast, easy access time, they pose their own unique challenges; the small screen size (necessary of a device placed on the wrist) has implications for usability [131-133] (for example, readability, input, etc.); there are limitations placed on interactions [133]; there are privacy issues surrounding the displaying of personal information visible for all to see; both hands are effectively occupied when interacting with the device (one that has the device placed on the wrist and the other required to interact with it); and using two hands to interact with the device may be difficult while walking [134]. However, wrist based interfaces are advantageous in that both hands are free when the user stops using it, and the user is not required to put away a device [135].

Researchers have also explored small, subtle form factors that provide always available, easily accessible and interruptible input in the form of ring-based or finger-worn devices, for example: iRing [136], Nenya [135], Magic Finger [137]. Typically these devices still require the use of one or both hands while performing the interaction (Nenya [135] performed better when used with both hands) and are often restrictive in the amount of input provided [6]. N-fingers [89], a glove like device has four buttons positioned on the index, middle and ring fingers allowing for the mapping of one action per button (four in total). Similarly, voice and gesturing input are typically restricted to a limited set of commands (for example: WatchIt [130] offers up to 15 gestures) and are typically not usable without specifically tailoring applications for their use. Gesturing systems may also require extra or special sensing equipment (for example: SixthSense [75, 76] uses a hat mounted camera and projector, OmniTouch [84] places the camera and projector on the shoulder). Typically these input modalities map directly to specific actions rather than providing a continuous signal that can be used for general purpose direct manipulation [4]. In addition, the above also typically tightly couples the task and the device and does not necessarily provide general-purpose interaction.

In light of the above discussion, it is evident that input modalities for wearable computers remains a key challenge. Given that wearable computing is a relatively new discipline, there does not yet exist a standardised way of interacting with a wearable computer in contrast to desktop computers where a keyboard and mouse are the standard, typical and assumed devices. With the imminent release of new wearable technology poised to hit mainstream markets, research into wearable interaction continues to be essential and timely.

2.3.1 Non-commercial Devices for Pointing Interaction

Pointing is fundamental to most human-computer interactions [2, 5]. A mechanism for continuous pointing suitable for use with wearable computing is vital [4, 5] as various forms of wearable computing are adopted. The prolific use of Graphical User Interfaces and the WIMP metaphor found on desktop computers typically requires the use of a pointing device in order to interact with the system. Users who wish to run their desktop applications on their wearable computers [3] will likewise require the use of a suitable pointing device given that the interaction metaphor remains the same. Researchers have

explored different means by which to perform command entry and cursor control in a wearable system.

Rosenberg [138] explores the use of bioelectric signals generated by muscles in order to control an onscreen pointer. Using electromyogram (EMG) data of four forearm muscles responsible for moving the wrist, the Biofeedback Pointer allows the control of a pointer via hand movements (up, down, left, right). The intensity of the wrist movement and therefore generated muscle activity is responsible for controlling the velocity of the pointer. In a user study where three participants carried out point and select tasks, the Biofeedback Pointer was found to perform an average of 14% as well as the standard mouse it was being compared to.

An acceleration sensing glove (ASG) was developed by Perng et al. [139] using six, 2-axis accelerometers with a wrist-mounted controller, RF transmitter and battery pack. Five accelerometers were placed on the finger tips and one on the back of the hand. The accelerometer placed on the back of the hand operated as a tilt-motion detector which moved an on screen pointer (on a Windows 95 or NT machine). The thumb, index and middle fingers were used to perform mouse clicks by curling the fingers. The glove could also be used to recognize gestures.

SCURRY [88] is another example of a glove like device worn on the hand and is composed of a base module (housing two gyroscopes) and ring modules which can be worn on up to four fingers (housing two acceleration sensors each). The base module provides cursor movement and the ring modules are designed to recognise finger clicks. When a ring module is worn on the index finger, SCURRY performs as a pointing device. SCURRY was evaluated against a Gyration optical mouse and was found to perform similarly.

FeelTip [140] is a wrist mounted device (worn like a watch) consisting of an optical sensor (Agilent ADNS-2620) that is placed just below a transparent plate with tip for tactile feedback. Moving a finger (index or thumb) over the tip moves the mouse cursor and pressing on the tip in turn presses on the switch (that is located under the optical sensor) and triggers a left mouse click. The authors evaluate the device against an analogue joystick across four tasks, pointing, 1D menu selection, 2D map navigation and text entry. The FeelTip performed better than the joystick for the menu and map navigation tasks.

For the pointing task over the five days, the average throughput was 2.63bps for FeelTip and 2.27bps for the joystick.

FingerMouse [141] is a small-sized (43mm x 18mm) visual input system designed to control a mouse pointer by tracking the in-air movements of the user's hand. The device can be worn attached to the user's chest or belt.

Oakley et al. [5] evaluated a pointing method using an inertial sensor pack. The authors compare the performance of the pack when held in the hand, mounted on the back of the hand and on the wrist. The experimental conditions were presented on a 24inch flat panel display positioned one meter from the participants. Participants undertook the experiment while standing. The results reveal that the held position performed better than the wrist. Although exact throughput values are not reported, it appears from the graph that the hand positions were just over 3bps and the wrist performing just under.

Tokoro et al. [3] explored a method for pointing instrumented by two accelerometers attached to the body, for example, the thumbs or elbows, etc. Cursor movement and target selection was achieved by the intersection of the two axes as a result of accelerometer positioning. In a comparative study, the authors found that the trackball, joystick and optical mouse performed better than the proposed accelerometer technique. The targets were 64 x 64 pixels and presented on a PC monitor. The authors also introduce an icon placement strategy in order to better suit the proposed accelerometer approach. Horie et al. [142] build on this work by evaluating the placement of the accelerometers on different body parts, (i.e. index finger, elbow, shin, little finger, back of hand, foot, thumb and middle finger on one hand, wrist and head and hand) and under the different conditions (i.e. standing with both hands occupied, standing with one-hand occupied, and sitting with both hands occupied). The authors also included a Wii remote and a trackball in the evaluation. Selection is achieved by maintaining the cursor over a target for one second for the accelerometer conditions and the Wii remote. Participants wore a monocular head-worn display. Participants were evaluated over seven days. Results show a stabilizing of performance on the third or fourth day for all conditions except for the shin and wrist which took longer to stabilise and the trackball which stabilised following day one. The authors found that the trackball and Wii remote performed better than the accelerometer conditions. However, the authors conclude that any of the proposed conditions may be used for pointing and are advantageous due

to the fact that the user does not have to hold a device in order to use the accelerometer method.

Calvo et al. [143] developed a pointing device called the G3 which is designed to be used by United States Air Force dismounted soldiers. Small wearable computers are being used by the special tactics dismounted operators for mission objectives. Traditional pointing devices such as a touchpad or trackpoint are embedded into the small wearable computer in order to control the device. The authors state that interacting with the pointing devices (touchpad and trackpoint) that are currently embedded into the small wearable computer requires the soldiers to wear the wearable computer on their chest. This has certain limitations as certain positions or situations prevent the soldiers from reaching their chests, for example when prone or when holding a weapon. In light of this, the authors designed, implemented and evaluated the G3. The G3 consists of a tactical glove that has a gyroscopic sensor, two buttons and a microcontroller attached to the index finger, the side of the index finger and the back of the glove respectively. The gyroscopic sensor (attached to the tip of the index finger) is used for cursor movement, however, the cursor will only move if one of the buttons is being held down, this is employed to avoid inadvertent cursor movement. The other button performs a left-click. The authors evaluated the G3 against the touchpad and trackpoint which are embedded into the General Dynamics operational small wearable computer (MR-1 GD2000). This appears to be one of the few studies that uses Fitts' law in a wearable context following the recommendations made by Soukoreff and Mackenzie [13] which support and supplement the ISO 9241-9 standard. Participants wore the small wearable computer on a tactical vest and undertook multidirectional tapping task as described in the ISO 9241-9 standard. Distance (128, 256, 384, 512 pixels) and width (35 and 45 pixels) values were chosen to be appropriate for the MR-1. The authors reveal that the G3 performed with a throughput of 3.13 bps (SD 0.22), movement time of 1024.43 (SD 54.90), and an error rate of 15.51 (SD 1.12). Movement time units do not appear to be reported by the authors. The touchpad performed with a throughput of 2.46 bps (SD 0.15), movement time of 1329.13 (SD 85.93), and an error rate of 3.29 (SD 0.77). The trackpoint performed with a throughput of 1.49 bps (SD 0.07), a movement time of 1997.64 (SD 98.28), and an error rate of 11.05 (SD 1.44). The G3 had a higher throughput and performed faster than its two counterparts but less accurately. The authors [143] state that it is suitable for use by dismounted soldiers wearing small wearable computers.

With the release of wearable glasses-based displays that are smaller, less obtrusive and targeted towards the consumer market, research into suitable, subtle and socially acceptable interaction with head-worn displays is vital. Interest in input devices and interaction for head-worn displays is growing as evidenced by the following researchers who have designed input devices with the intention of being used with a head-worn display.

Attaching a magnet to the back of the thumb and two magnetometers to the back of the ring finger, Chen et al. present uTrack [4], a 3D input system that can be used for pointing. Users move the thumb across the fingers in order to control an onscreen cursor. In an evaluation performed while participants were seated in front of a monitor, the authors found that participants were able to use uTrack for cursor control tasks and the technique was well received.

FingerPad [6] is a nail mounted device that allows the index finger to behave as a touchpad. The system is implemented via magnetic tracking by mounting a magnetic sensing plate and a neodymium magnet to the index finger and thumb respectively. When the fingers are bought together in a pinching motion, the index finger becomes the touchpad and the thumb may be used for interactions such as pointing, menu selections, and stroke gestures. The authors evaluated the device via a point and select user study measuring trial completion time and error rate. Participants were asked to move an on screen cursor to a target and select it using either a thumb flick gesture or a click technique with the opposite hand. Users evaluated the system while sitting at a desk and walking on a treadmill. During both conditions a laptop was used in order to present the experimental conditions to the participants. Interestingly, the authors did not find a significant difference between the walking and seated completion times, however noted a significant difference of error rate between the walking and seated completion times when target size was below 2.5mm. The flick gesture required for selecting targets performed significantly slower than the click method in the walking condition only. Across both movement conditions, the target size of 1.2mm performed significantly slower than the 5mm and 10mm target sizes; while the 0.6mm target size performed slower and with more errors than the other target sizes (1.2mm, 2.5mm, 5mm and 10mm).

Kato and Yanagihara [1] introduce PACMAN UI, a vision-based input interface also designed to be used as an input technique suitable for use with a head-worn display. Users form a fist and position the index finger and thumb to form the letter C (i.e. a Pacman shape). Doing so exposes the middle finger which is used to control an onscreen cursor. Moving the middle finger causes the onscreen cursor to move accordingly. Users click by pinching the index finger and thumb together. Empirical results found the PACMAN UI to be 44% faster than the wireless mouse it was being compared to.

2.3.2 Non-commercial Devices for Menu Interaction

Researchers have explored the development and use of dedicated input devices to interact with menus presented onscreen. The VuMan 1 [28], VuMan 2 [29], and VuMan 3 [30] series of wearable computer are examples of this and use dedicated input devices to interact with on screen objects. The VuMan 1 [28] system included a three-button input device. The centre button of the input device was used to select icons at the bottom of the screen while the outer two buttons were used to select the functionality within the selected icon. Interaction with the VuMan 2 [29] system was also via a three-button mouse which allowed the user to select items (the buttons mapping to different screen dependent commands) and move an on-screen cursor. The input device was designed to be held in the hand or mounted on the user's body. The VuMan 3 [30] iteration introduced a rotary dial input device (with selection buttons situated around the dial) [31] that was embedded in the housing of the computer. The dial drove the design of the interface. Menu/list items were selected by turning the dial (in either direction) and selecting via the buttons surrounding the dial [31, 32]. A descendent of the VuMan 3 [31] was later designed with multiple possible input devices in order to support different applications – a dial and a circular touchpad that was to be used when the dial was not appropriate.

Cross et al. [144] implemented a pie-menu interface to support minimal interaction for the military undertaking urban operations. The system included an x4 wearable computer, a Micro-Optical display and a three button input device (up, down and select).
Blasko and Feiner [145, 146] presented a menu interface prototyped by a TouchPad device. The device is separated into four strips, each which correspond to a finger of the hand. Four top-level menus are presented at the bottom of the screen. The on-screen

menu is designed to be used specifically with the device, whereby each strip corresponds to a menu.

KeyMenu [147] is a pop-up hierarchical menu which uses the Twiddler input device to provide a one-to-one mapping between buttons on the keyboard and the menu items presented on the screen. The menu is displayed in a grid of three columns and four rows. Pressing a key on the Twiddler activates the corresponding menu item.

Although the input modalities presented thus far (in this and the preceding sections) are compelling in their application to wearable computing, they typically require specialised hardware and/or software to operate. The modalities mostly provide discrete input that may be directly mapped to a specific action. Also, the form factor of the device may be tailored to suit a particular task. Without the ability to implement specialised hardware and/or software, users need to turn their attention to commercially available devices as a means to provide suitable wearable interaction. Users may also wish to run current applications on a wearable device. To this end, the requirements for textual data and command entry remain the same as a desktop system where this is typically performed by the keyboard and mouse respectively. In light of this, users instead need to make use of commercially available input devices that can be used without having to be constructed or having to install specialised software. The input devices must be suitable for use with wearable computers and provide general-purpose input. The following section explores commercial pointing devices suitable for use with wearable computers.

2.3.3 Commercially Available Pointing Devices

There exist a number of commercially available input devices suitable for use with wearable computers, that can be grouped into the following categories: devices specifically designed for text entry (WristPC[39]), devices designed for cursor control (outlined below) and devices capable of performing both functions (iKey AK-39/AK-39-NV)[40], FrogPad [41], Twiddler2[42]). Four commercially available pointing devices have been identified as follows: handheld trackball, touchpad, gyroscopic mouse, and Twiddler2 mouse. Although there may be a number of different models of these devices, they

[39] http://www.l3sys.com/wristpc/wristpc.html
[40] http://www.ikey.com/product/ak-39/
[41] https://web.archive.org/web/20131027142139/http://www.frogpad.com/magic-frogpad.php
[42] http://www.handykey.com/

operate in a similar fashion. All four devices provide the user with the ability to perform general cursor movement, object selection, and object drag and drop and all four devices may be used with either the left or right hand. The devices can be used in place of a traditional desk-top mouse. The devices were chosen due to the following reasons; their suitability for use with wearable computers; their use was noted in the wearable research literature; and they are representative of the commercial devices available for cursor control and command entry. Additionally, the devices provide general-purpose interaction suitable for use with wearable computers and are readily available as commercial, off-the-shelf products.

2.3.3.1 Trackball

The 4D Off-Table Hand Track[43] mouse referred to as the trackball device is a product of 3G Green Green Globe Co, Ltd. There are a number of variations available of this device with differing number of buttons, shape and length of handle, and with no trigger guard, however they all operate in a similar fashion. The 4D Off-Table Hand Track trackball device has a trackball (1.9 cm diameter) situated on the top of the device that is manipulated with the user's thumb to perform cursor movement. The device integrates three mouse buttons: a trigger button for left clicks (index finger operation), and two buttons (thumb operation) on top of the device providing the user with the ability to right and left click. Selection of targets is performed by pressing the trigger button. In order to perform a drag and drop operations, the user is required to press the trigger button to select the target, move the cursor using the thumb (trackball) and release the trigger once the object is repositioned (on the destination target). Figure 4 demonstrates the device and the position of the device in the user's hand.

Two trackballs are used as a text entry technique via a double pie menu method [148]. A hand held trackball was used to interact with Chi-3 [38, 39] which ran the Windows 95 operating system providing the capability to run commercially available software. In Tinmith-Metro [45], users may choose a hand held trackball in order to perform 3D manipulation of graphical objects. A trackball was used to interact with a wearable navigation aid [149] displaying digital maps to the user via a MicroOptical monocular head-

[43] http://www.3g-tw.com/english/index_english.html

worn display. Lehikoinen and Röykkee [150] use a finger mouse (trackball) to select objects presented via a see through head-worn display.

a)  b) 

Figure 4: a) 4D Off-Table Hand Track mouse referred to as the trackball device. b) Device positioned in the hand

2.3.3.2 Touchpad

The EasyCat Touchpad[44] seen in Figure 5 is a portable version of a TouchPad found on many notebook computers. Cursor movement is achieved by moving the user's finger along the pad. Selecting of targets is performed by either double tapping on the pad, or by using the left click button. Dragging and dropping of targets is performed by either double tapping on the pad to select a target, or by holding the left click button down (with the thumb) while moving the finger along the pad. The touchpad is attached to the user's forearm for the studies undertaken in this dissertation. The forearm position was chosen as a result of our previous study [151, 152], as it reported one of the fastest mean times and was preferred by users. An elastic and Velcro strip was added to the device to allow it to be secured to the participant's forearm (as seen in Figure 5).

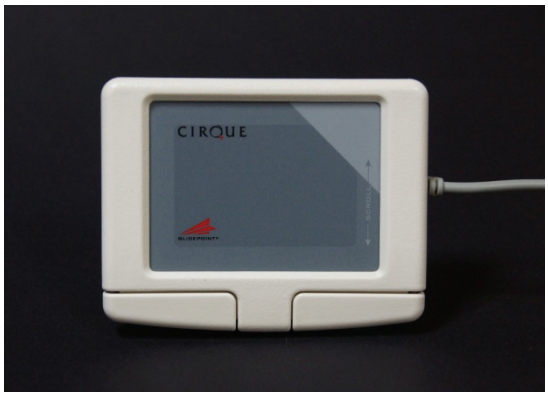
a)  b) 

Figure 5: a) EasyCat Touchpad (Cirque). b) Secured to forearm via elastic and velcro strip

[44] http://www.cirque.com/

The touring machine [41] used the Cirque GlidePoint trackpad mounted on the back of a handheld computer in order to control the menu displayed in a head-worn display.

2.3.3.3 Gyroscopic Mouse

Gyration Ultra GT[45] cordless optical mouse referred to as the gyroscopic mouse is a product of Gyration Inc. The gyroscopic mouse has an activation trigger which enables cursor movement, two mouse buttons (left and right) and a scroll wheel. To move the cursor, users must press and hold the activation trigger with their index finger while moving their wrist up, down or sideways. The mouse senses relative hand motion, and as a result, the cursor follows the motion of the user's hand. Selection of targets is performed by pressing the left mouse button. Dragging and dropping of targets is performed by first selecting the target by pressing the left mouse button, moving the cursor to the destination target using hand movements and dropping the target by releasing the left mouse button. Figure 6 demonstrates the position of the device in the user's hand, with the index finger on the activation trigger.

a)  b) 

Figure 6: a) Gyration Ultra GT cordless optical mouse referred to as the gyroscopic mouse. b) Device positioned in the hand

A gyroscope-equipped mouse is used in the Battlefield Augmented Reality System [50] to select objects. A gyroscope-equipped mouse is also used in the authoring of models [51] as a pointing device to select points. Dragging the mouse up, down, left and right changes the user's position and orientation in the model.

[45] http://www.gyration.com/

2.3.3.4 Twiddler2

The Twiddler2[46] is a product of the Handykey Corporation. Unique to the Twiddler2 is the ability to perform both text entry and cursor control. Text entry is performed via the one-handed chording keyboard consisting of twelve keys (arranged in three columns and four rows) on the front of the device. However, for the purpose of the studies undertaken as part of this dissertation, only the cursor control and mouse button functionality of the device are utilised. A fabric strap wraps around the back of the hand to hold the Twiddler2 in position. The IBM Trackpoint [153-155] is an isometric joystick that is situated on the top/back of the device and is operated by the user's thumb. An isometric joystick is force-sensing meaning that the force applied to the joystick controls the speed at which the cursor moves. Moving the Trackpoint under the thumb moves the cursor in the direction of the applied force and places the Twiddler2 into mouse-mode. In mouse-mode, the front keys function as mouse buttons. Selection of targets is performed by either pressing the 'A' or 'E' key. Drag and dropping of targets is performed by either pressing the 'A', 'D' or 'E' key. The A key is the left click mouse button. It exits mouse-mode when released. The E key is also a left click button, the difference being that it stays in mouse-mode after it is released. Performing a drag and drop operation with the A and E key requires the user to hold the A or E key down while moving the Trackpoint to position the target. When the target is in position, the user is required to release the A or E key. The D key emulates a left mouse button being held down. Performing a drag and drop operation with the D key requires pressing D to select the target, moving the Trackpoint to position the target and pressing D again to release the target (releasing D after the second press of the key causes the Twiddler2 to exit mouse-mode). Note that unlike the A and E key, the D key is not required to be held down while moving a target. The Twiddler2 is seen in Figure 7.

The Twiddler2 has been used as an input device in the following research; 3D navigation methods [156], the Remembrance Agent [20, 36], MIThril [58], KeyMenu [147], and in everyday use [8, 157].

[46] http://www.handykey.com/

a) b)

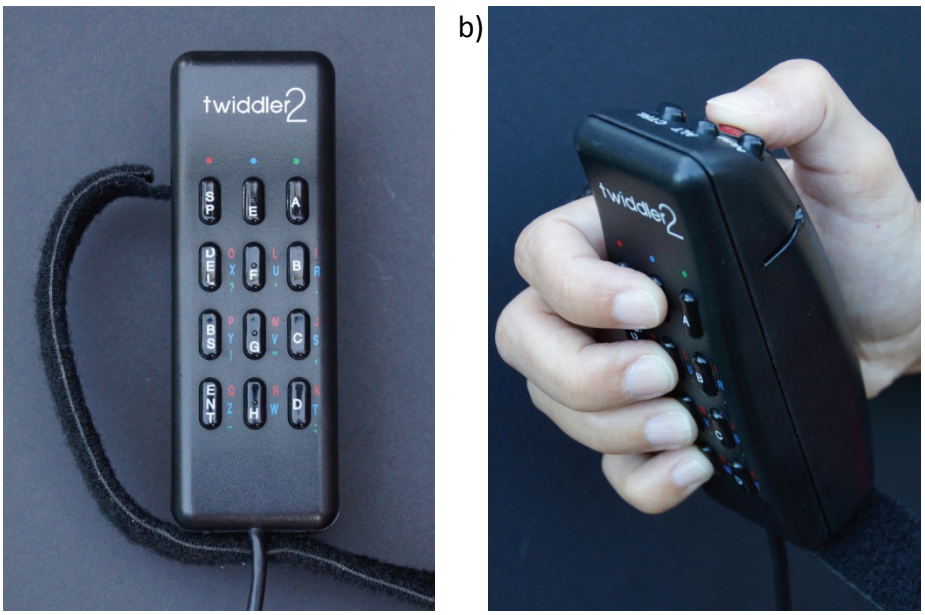


Figure 7: a) Twiddler2. b) Device positioned in the hand

2.3.4 Section Summary

Effective input devices and interaction techniques are essential to the usability of a wearable computing system. Given that many of the traditional input devices cannot be used effectively in a wearable scenario, many wearable computing prototypes employ their own particular input mechanisms or adopt variations of well-known input paradigms prevalent in desk-based computer interaction. Without access to specialized software or hardware, wearable systems may make use of commercially available products such as Microsoft Windows, existing applications and input devices. In light of this, the requirements for textual and command entry remain the same as a desktop system where this is typically performed by the keyboard and mouse respectively. Although it may be found that optimal interaction methods for wearable computers may differ from those used in desktop computers, it is important to evaluate the currently available input devices, not only as a means to empirically determine their usability within a wearable context and inform and guide users of the technology when deciding amongst devices, but to also provide a basis on which to inform and guide design so that usable and effective input devices irrespective of interaction metaphor can be created.

Early wearable computing users and adopters of the technology [8, 20, 21, 157] typically wore a head-worn display of sorts and in some cases, have been wearing them ever since as part of their everyday use [66, 158]. Head-worn displays offer immediacy [8, 66], that is, information is always available at a glance. Information displayed in a head-worn

display is private to the user. Head-worn displays also allow the user to be aware of her surroundings, keeping her head-up so that focus on her primary task can be maintained. Together, these offer compelling reasons for the use of a head-worn display in a wearable system and therefore was naturally chosen as the form factor to display information for the user studies undertaken as part of this dissertation. This dissertation explores interactions where the information displayed is fixed to the head-worn display [159] irrespective of the user's position or orientation. How to effectively interact with the information presented via a head-worn display is for the most part an unsolved problem. Pointing is a fundamental operation undertaken in current graphical user interfaces [160, 161] and although pointing devices have been studied extensively in traditional desktop machines, studies evaluating pointing devices for use with wearable computers are rare. This dissertation evaluates the use of commercially available pointing devices suitable for use with a wearable computer. The next section describes the evaluation methods used in this dissertation in order to ascertain the usability of the four pointing devices mentioned in section 2.3.3.

2.4 Evaluation Methods for Pointing Devices (Usability)

Usability is multidimensional in nature [12] and is associated with the following five attributes identified by Nielsen as; learnability, efficiency, memorability, errors and satisfaction. The ISO 9241-11 standard which describes ergonomic requirements for office work with visual display terminals [162] defines usability as the "extent to which a product can be used by specified users to achieve specified goals with effectiveness, efficiency and satisfaction in a specified context of use". Part 9 of the ISO 9241 [11] standard applies the definition of usability to non-keyboard input devices, and identifies the following guiding principles with regard to input device efficiency, effectiveness and satisfaction;

- Efficiency: "an input device is most efficient when it functions with the least amount of time and effort" [11].
- Effectiveness: "a device is effective when its design takes into consideration factors that lead to enhanced or optimized user performance by means of accuracy and completeness" [11].

- Satisfaction: "an input device design is satisfactory when its design incorporates factors that lead to freedom of discomfort and enhance positive attitudes of users towards its use" [11].

An input device is considered useable if users can achieve a satisfactory level of performance on a given task and maintain an acceptable level of effort and satisfaction [11]. Usability testing evaluates efficiency, effectiveness, and satisfaction in a specific context [11, 162]. The usability of the four pointing devices mentioned in Section 2.3.3 are evaluated by adopting the usability measures defined in the ISO 9241-9 listed above. The ISO 9241-9 [11] standard outlines a methodology for evaluating performance (efficiency and effectiveness) and comfort (satisfaction).

2.4.1 Traditional Input Devices and Interaction Technique Evaluation

Usability studies investigating traditional input devices and interaction techniques have measured performance by comparing the speed and accuracy between devices in order to determine differences and improvements. A typical task is to point and select a graphical object on a computer monitor.

2.4.1.1 Target Selection and Drag and Drop User Studies

Performance of traditional input devices has been measured by comparing speed and accuracy between devices to determine differences and improvements. An example is the experiment conducted by MacKenzie et al. [161] comparing the speed and accuracy of three input devices, a mouse, a trackball and a stylus with tablet for pointing and dragging tasks. Across the devices, dragging tasks were more error prone and were slower than pointing tasks. The trackball was the slowest device in both the pointing and dragging tasks. The mouse and stylus performed comparably in the pointing task, however, the stylus performed faster than the mouse in the dragging task. The devices performed comparably with regards to errors in the pointing task, while for dragging, the mouse performed with fewer errors and the trackball performed with the most errors. In the case of evaluating an input device or technique, a customary task is to point and select a graphical object on a monitor. An example is the study by MacKenzie and Jusoh [163] performing a standardized comparison of two remote pointing devices, GyroPoint-air and

RemotePoint, for selection tasks. Participants carried out a point-select task which required them to move a cursor back and forth between two targets selecting them by pressing and releasing a button on the device. The investigation employed a standard mouse as a base-line condition. The two remote pointing devices performed poorly compared with the mouse.

2.4.1.2 Menu Selection User Studies

Mitchell and Shneiderman [164] compared dynamic and static menus using performance measures of average total time taken and average number of errors made to complete 12 menu selection tasks and found that initially dynamic menus were significantly slower than static menus. However, a small amount of practice reduced the performance difference to a non-significant level. Participants preferred using static menus.

A comparison of selection times for walking and pull-down menus found that the time required to access items from a pull-down menu was less than that required for a walking menu [165]. This study showed that while the use of impenetrable borders and expanding target areas facilitated menu selection, the impenetrable borders were the most effective in decreasing menu selection time.

Callahan et al. [166] evaluated pie and linear pop-up menu configurations of eight items using an optical mouse. Target seek time (the time taken to invoke the menu via mouse button press, move to the target item and select it by releasing the mouse button) and the number of errors are measured. Pie menus were found to perform faster and with fewer errors than the linear menus. Interestingly, participant subjective results did not overwhelmingly favour one menu over the other.

Ahlström et al. [167] conducted a study evaluating two menu selection techniques known as Jumping Menus and force enhanced menus using traditional pull-down menus as a benchmark. The authors found that Jumping Menus produced the most errors. The force enhanced menu enabled users to complete their tasks faster than the Jumping Menu. Both menu techniques performed faster than the standard menu. Participants' subjective feedback shows preferences for the Jumping Menu and the force enhanced menu.

Cockburn and Gin [168] evaluated a menu selection technique to improve the selection of items in cascading menus. The selection time taken from the posting of the top-level menu to successful target acquisition and number of errors are logged and reported.

Compared with traditional menus, enlarged activation area menus allowed cascade items to be selected up to 29% faster.

The performance of static, adaptive and adaptable menus were evaluated by comparing the dependent measures of speed and error rate. Findlater and McGrenere [169] found that static menus were significantly faster than adaptive menus. Effects due to the order in which the menus were presented to participants identified the following; where the adaptable menu was presented first, it was found that the adaptable menu was slower than the static menu and not statistically different from adaptive menus. Where the adaptable menu was not presented first, the authors found it was faster than the adaptive menu but not significantly different from the static condition. Participants preferred the adaptable menu design.

2.4.2 Fitts Law Testing of Pointing Devices

Fitts' law describes human motor performance for people engaged in rapid aimed movements [13]. Fitts [170, 171] applied information theory to the area of human performance in order to determine the information capacity of the human motor system [172]. The human motor system is responsible for producing an action. Fitts proposed the human motor system as a communication channel where movement amplitude (or distance) corresponds to the signal and target width represents the noise [13, 173]. When performing a movement task, bits of information are transmitted via this human channel [172]. The proposition by Fitts [172] states that the human motor system transmits bits of information when performing a movement task. Fitts sought to measure the rate at which information is transmitted by the human motor system when performing a movement task [172] and therefore determining the information capacity of the human motor system. Fitts terms the information capacity (information transmission rate) of the human motor system the 'Index of Performance' (IP). In measuring the rate of information processing (task execution rate), we can infer the information capacity of the human motor system [173]. A high Index of Performance (IP) represents a large capacity (rate of transmission) [173].

Movements are assigned a task difficulty dependent upon the distance (or amplitude) of movement to the target, and the width of the target. Task difficulty is termed 'Index of

Difficulty' and is measured in bits. The number of bits represents the information transmitted when performing a movement task [174].

Fitts' [170, 171] calculated the index of difficulty [172] for a movement task as:

$$ID = log_2 \left(\frac{2A}{W}\right) \quad (1)$$

where A is the amplitude (or distance) to the target and W is the width of the target.

Fitts' law states that there is a linear relationship between task difficulty (ID) and movement time [173]. Targets that are larger and are closer together can be selected faster than targets that are smaller and further away from each other. That is, as task difficulty increases (either by increasing the distance between targets or by decreasing the target width), the time taken to select the targets also increases (that is, more time is required to perform the task) [175].

The Index of Performance (IP) is calculated by dividing the difficulty of the task (Index of Difficulty, ID) by the Movement Time (MT) taken to perform the task [172].

$$IP = \frac{ID}{MT} \quad (2)$$

Dividing the average number of task difficulty bits (bits per movement) by the average time per movement results in the rate of information transmission (in bits per second) [170-172]. Fitts [170, 171] stated that the information transmission rate remains relatively constant over a range of task difficulty conditions. A high value of IP represents the fact that more information is being transmitted per second resulting in a higher rate of performance [175]. The opposite is true for low values of IP.

Fitts' [170, 171] original research was a serial tapping task which required participants to tap between two metal plates using a stylus, a disc transfer task and a pin transfer task. Although Fitts' law [170, 171] was first described in literature in 1954 and successfully applied to a variety of domains [176], it was not until 1978 that the seminal work of Card, English and Burr [177] applied the model to the field of HCI [175]. This was the first application of Fitts' law to the field of HCI and the first evaluation of the mouse against other devices [178]. Card et al. [177] evaluated a mouse, a rate-controlled isometric joystick, step keys and text keys to determine how quickly they can be used to select text on a CRT. The mouse was found to perform the fastest and with the lowest error rate for

text selection. In the work of Card et al. [177], positioning time for the mouse and joystick is modelled by the Welford formulation of the index of difficulty (ID).

$$ID = log_2 \left(\frac{A}{W} + 0.5\right) \quad (3)$$

The work proposed by MacKenzie [172, 179] further refined the formulation of index of difficulty and introduced what is commonly known as the Shannon formulation of ID (where D is the distance (or amplitude) to the target and W is the width of the target).

$$ID = log_2 \left(\frac{D}{W} + 1\right) \quad (4)$$

Since its first appearance [172, 174, 179] in research literature, the Shannon formulation has been used extensively in the field of HCI. The Shannon formulation is preferred for ID [175] as it has a better fit with data, yields a positive value for ID and closer resembles the information theory from which Fitts' work was derived [13]. The preference for the Shannon formulation is well documented [13, 172, 174, 179, 180]. The Shannon formulation of ID is included in the ISO 9241-9 (Ergonomic Requirements for Office Work with Visual Display Terminals (VDTs) - Part 9: Requirements for Non-Keyboard Input Devices)) standard [11] which seeks to establish consistent guidelines and testing protocols for the evaluation of non-keyboard input devices (for example pointing devices). The use of D (distance) in the Shannon formulation of ID as seen above instead of A (amplitude) is in keeping with the ISO 9241-9 [11] standard.

In light of the many formulations for ID and the differing ways of calculating IP (via division of means or via regression model), Soukoreff and MacKenzie [13] advocate for the consistent application of Fitts' law and make recommendations as a means of achieving this. The authors argue that a consistent application of Fitts' law will allow findings to be compared across research studies published in literature [13]. This has typically been problematic given the many varied applications of Fitts' law [13]. The recommendations proposed by Soukoreff and MacKenzie [13] support and supplement the methodology prescribed in the ISO 9241-9 standard. In light of this, Fitts' law has been applied in this dissertation adhering to the ISO 9241-9 standard [11] along with Soukoreff and MacKenzie's [13] recommendations where applicable, for example, use of the Shannon formulation of ID, use of a wide and representative range of ID values, adjustment for accuracy to use IDe values instead of ID values, use of linear regression to

measure goodness of fit (that is, whether Fitts' law applies), calculation of throughput via the mean of means rather than the reciprocal of the slope of the regression line ($1/b$).

Index of Performance (IP) commonly called Throughput as per the ISO 9241-9 [11] standard is calculated as follows:

$$Throughput = \frac{Effective\ index\ of\ difficulty}{Movement\ time} = \frac{ID_e}{MT} \quad (5)$$

where ID_e is the effective index of difficulty.

The index of difficulty presented above (in equation (5)) is replaced by the effective index of difficulty which is calculated as follows:

$$ID_e = log_2\left(\frac{D}{W_e} + 1\right) \quad (6)$$

where W_e is the effective width and is calculated by measuring the distribution of selection coordinates (endpoints) made by a participant over blocks of trials. That is, adjust the target width based on the distribution of selection coordinates (hits) [175]. The standard deviation of selection coordinates reflects the overshoot or undershoot for the movement in the direction of motion [11, 13]. It is used to perform the adjustment for accuracy for each participant. Because participants will perform the tasks with differing speeds and accuracies, it captures how the participant actually performed. The standard deviation of the selection coordinates is calculated to define the effective target width as follows:

$$W_e = 4.133 \times SD_x \quad (7)$$

Effective target width is used to calculate the effective index of difficulty as seen above. This corrects the ID values so that they represent the movements that the participants actually performed [13]. It accounts for slow but accurate movements in contrast to fast but less accurate movements performed by participants. Participants selecting targets have been shown to produce selection coordinates (endpoints) that conform to a normal distribution [13, 172]. The constant term of 4.133 is derived from the amount of endpoint entropy in a normal distribution [13, 14, 172], defined as ($log_2\left(\sqrt{2\pi e}\sigma\right) = log_2\left(4.133\sigma\right)$ [172]). The adjustment for accuracy is designed to normalise the target widths, where the effective target widths are representative of the spread of data [13].

The adjustment for accuracy was proposed by Crossman and is well documented in the following [13, 172, 174, 175, 179].

Given the adjustment for accuracy, throughput is therefore a measure that combines both the speed and accuracy of the participant when calculated using effective index of difficulty. Throughput is therefore a measure that combines both the speed and accuracy of the movement performance [13]. Throughput is independent of the speed-accuracy tradeoff [181]. Throughput reflects the efficiency with which the participant was able to accomplish the task [163]. It stands to reason then, that the larger the value of throughput for a device, the faster it will perform [16]. If devices follow Fitts' law, we can then use the dependent measure of throughput as a means for comparison [13]. As previously mentioned, throughput can be calculated in two ways; via the reciprocal of the slope of the regression line ($1/b$) and via the mean of means. In this dissertation, throughput is calculated via the mean of means as recommended by Soukoreff and MacKenzie (see paper [13] for detailed discussion) and adhering to the ISO 9241-9 standard [11].

A least-squares linear regression can be used to determine whether the model fits the data well, that is, do the devices follow Fitts law? In the Fitts' law equation (8) seen below, the intercept (a) and the slope (b) parameters can be found using a least-squares linear regression [13].

$$MT = a + b \times ID_e \tag{8}$$

This is used to determine whether there is there a linear relationship between movement time and ID and therefore to determine whether Fitts' law applies [13].

Fitts' law is a robust and widely adopted model which has been successfully applied to a variety of domains [176]. Fitts' law has been used extensively throughout HCI research. Typically, Fitts' law has been used to derive the dependent measure of throughput which allows comparisons between different devices across studies to be made (obtainable when throughput is calculated the same way). Previous work evaluating different input devices is outlined below (and summarised in Table 1).

Douglas et al. [182] evaluate two pointing devices for laptop computers, an isometric joystick and a touchpad. The joystick performed with a faster mean movement time

(1.975 seconds) and lower error rate (2.1%) than the touchpad (2.382 seconds, 5.4%). The joystick (2.15 bps) performed with a 27% higher throughput than the touchpad (1.70 bps). Participants reported that the joystick required more force to operate than the touchpad.

Two pointing devices suitable for use in remote pointing tasks such as interactive TV, presentations, etc. are evaluated by MacKenzie and Jusoh [163]. A total of four pointing devices are evaluated; GyroPoint-air (a handheld device containing a gyroscope which allows in air operation), RemotePoint (a handheld device which contains an isometric-joystick operated with the thumb), GyroPoint-desk (the aforementioned GyroPoint device can also function as a regular mouse when placed on a desk), and a traditional mouse used as a baseline condition. The two examples of remote pointing (GyroPoint-air 2.8 bps, RemotePoint 1.4 bps) were outperformed by the desktop pointing devices (GyroPoint-desk 4.1 bps, standard mouse 3.7 bps).

MacKenzie and Oniszczak [183] compare three selection techniques for touchpads. The selection methods include; using a physical button, using the lift-and-tap technique and a new technique that combines finger pressure with tactile feedback. The highest throughput was reported in the tactile condition at 1.43 bps, followed by the lift-and-tap 1.07 bps. Using a button observed the lowest throughput at 0.99 bps.

In a study evaluating six different sized mice, Isokoski and Raisamo [184] found that there was a small difference in the throughput between the devices ranging from 4.416 bps to 4.635 bps. Using the ISO 9241-9 standard, MacKenzie and Soukoreff [178] provide an updated analysis of Card, English and Burr's [177] original work. As a result of the reanalysis conforming to the ISO 9241-9 standard, the authors found that the mouse results in a throughput of 2.65 bps or 4.32 bps if adjusted slightly to account for the time taken to grasp the mouse. MacKenzie et al. [15] perform a comparative evaluation of four pointing devices. The authors found that the throughput for the mouse was 4.9 bps, 3.0 bps for the trackball, 2.9 bps for the touchpad and 1.8 bps for the joystick. The trackball and touchpad were not significantly different.

A novel input device called Swiftpoint [185] was evaluated against a traditional mouse and touchpad using a multi-directional point-select task as outlined by the ISO 9241-9 standard. In the pointing task, the mouse performed fastest (1.24s), followed by

Swiftpoint (1.61s) and lastly the touchpad (2.23s). The authors found that the throughput for the mouse was 4.05 bps, Swiftpoint 3.05 bps and the touchpad 2.38 bps. The touchpad performed with the most errors. The Swiftpoint and mouse were comparable in errors for low index of difficulty targets, however, for higher index of difficulty targets, the Swiftpoint exceeds both the mouse and touchpad. Participants preferred the mouse (73%) over the Swiftpoint device (26%).

Table 1: Fitts' law throughput values (summary of previous work described in this section)

Publication	Device	Throughput (bps)
Douglas et al. [182]	Joystick	2.15 bps
	Touchpad	1.70 bps
MacKenzie and Jusoh [163]	GyroPoint-desk	4.1 bps
	Mouse	3.7 bps
	GyroPoint-air	2.8 bps
	RemotePoint	1.4 bps
MacKenzie and Oniszczak [183] (touchpad selection techniques)	Finger pressure and tactile feedback	1.43 bps
	Lift-and-tap	1.07 bps
	Physical button	0.99 bps
Isokoski and Raisamo [184]	Six mice	4.416 – 4.635 bps
MacKenzie and Soukoreff [178] (updated analysis of Card, English and Burr's [177] work)	Mouse	2.65 bps and 4.32 bps (with adjustment)
MacKenzie et al. [15]	Mouse	4.9 bps
	Trackball	3.0 bps
	Touchpad	1.8 bps
	Joystick	1.8 bps
Amer et al. [185]	Mouse	4.05 bps
	Swiftpoint	3.05 bps
	Touchpad	2.38 bps
Natapov et al. [186]	Mouse	3.78 bps
	Wiimote	2.59 bps
	Classic controller	1.48 bps

Natapov et al. [186] evaluated two video controllers and a traditional mouse using a point-select task displayed on a television screen. The authors found that the mouse performed with a throughput of 3.78 bps, 2.59 bps for the Wiimote, and 1.48 bps for the Classic Controller. Participants preferred the Wiimote over the Classic Controller.

Not only can throughput be used to measure the rate of information transfer when a user is operating an input device [11], Fitts' law can also be used as a predictive model [175, 187].

Movement time predictions can be made using the following model [13]:

$$MT_{Predicted} = a + b \times ID \quad (9)$$

2.4.3 Workload - NASA Task Load Index

The NASA Task Load Index (NASA-TLX) is a multi-dimensional scale designed to obtain a subjective workload measure experienced by the subject when performing a given task [17]. The NASA-TLX is an easy to use and reliable measure of workload [188]. It has been used extensively beyond its original application of aviation [188] and is commonly used by the HCI community in order to evaluate the workload produced as a result of tasks undertaken for usability studies [10, 189-191]. The overall workload rating provided by the NASA-TLX is made up of the weighted average of six subscales; mental demand, physical demand, temporal demand, performance, effort and frustration [17]. Mental, physical and temporal demands relate to the demands imposed on the subject during the task. Mental demand measures the amount of mental and perceptual activity required for the task. Physical demand measures how much physical activity was required. Temporal demand measures the time pressure felt during the task [192]. Performance, effort and frustration relate to the interaction of a subject with the task [192]. Performance measures the perceived success of the subject in accomplishing the task. Effort measures how hard the subject had to work to achieve the level of performance. Frustration relates to how stressed or annoyed subjects felt during the task. Each scale is presented as a horizontal line divided from 0 to 100 by 21 vertical marks (in increments of 5). Each line contains descriptors at each end (low on the left and high on the right with the exception of performance which has good on the left and poor on the right). Subjects place a mark at the desired location that represents their experience during a task for

each of the six scales. If a subject marks between two vertical lines, the value to the right is used (i.e. rounded up). Once the rating for each of the six scales has been identified, subjects are then required to undertake 15 pair-wise comparisons (between each combination of scales) in order to ascertain which of the scales were important contributors to their experience of workload for a particular task. This forms the weight of each scale (0 being not very important to 5 being very important). The product of each rating and associated weight are summed and then divided by 15 (number of pair-wise comparisons) to form the overall workload for a particular task condition. The overall workload calculation results in a final score between 0 and 100 (0 being light workload and 100 being heavy workload). The overall workload result provides sensitive information pertaining to the workload associated with undertaking a task, while the individual scales (and weights) provide insight about the source of workload within a task [17]. The subjective measure of workload may provide valuable insights into the usability of an input device within a wearable context.

2.4.4 Longitudinal Evaluation

The value of longitudinal research is increasingly being recognized [193-195]. Longitudinal research can help answer questions such as identifying the transition from novice to expert (that is, how long does it take for users to reach an expert level of performance), learnability, comfort with technology, productivity, evaluation of user perceptions and abandonment or adoption rates [193]. Gerken et al. [196] suggest that longitudinal studies are a valuable tool in evaluating research questions such as: "How is users' domain knowledge expanding over time as a function of different tools or visualizations?", "How is the usability of the system perceived over time?", "How is performance influenced over time by users' individual differences?". Harada et al. [197] make use of a longitudinal study to determine whether there are any issues related to the usability of a device that perhaps had not been discovered due to the limited duration of usage by users [197]. Longitudinal research plays an important role in distinguishing between features that are unusable from features that take longer to learn [198] and in distinguishing between learning of the device and the task [199].

2.4.4.1 Longitudinal Evaluation of Input Devices

The value of longitudinal studies to evaluate input devices is demonstrated by the long history of studies reporting longitudinal results [177, 200]. In two case studies performed by Gerken et al. [199], the authors investigate the long-term usability of a laser pointer. In the first experimental study, they select six participants to use a laser pointer for five consecutive days (spanning 30-45 mins per day). The task is a modified discrete multi-directional tapping task. Each of the five sessions presented 756 trials per participant. In order to evaluate whether the learning translates to another task, they use a continuous one-directional tapping task. The authors used a post hoc Helmert contrast to determine the point in time when participants were fully trained. Analysis revealed that improvement was significant up to session three. In their second study, the authors conducted an experiment with 32 participants undertaking 1260 trials divided into seven blocks, but in one single session. A retention test was conducted with 12 of the participants returning to the lab 50 days after initial testing. The transfer task was the same as the experimental task but with smaller targets making the task more difficult. Learning was significant up to the very last block of trials.

Sporka et al. [201] undertake a longitudinal study of a non-speech audio input-controlled continuous cursor control system called Whistling User Interface (U3I). The system allows users to move a mouse by making a humming sound via a microphone. Depending on the length and pitch of the sound, the system moves the cursor accordingly. Clicking is achieved by making a short sound. Ten participants were evaluated. Experiments were conducted over five consecutive days. In each session participants were required to complete 16 training trials per target shape, 48 target acquisition trials per target shape. The independent variables were; target shape (bar, circle), target width (50, 100 pixels), approach angles (0, 45, 90, 135, 180, 225, 270, 315). Day 1 differed in that participants were required to fill out a demographic questionnaire. On day 5, participants were also required to perform 10 simple reaction time (SRT) tests. The SRT test aimed to identify how easy it was for expert users to click using U3I. The qualitative data suggests that participants opinions improved by the end of the study. Results of the study revealed that performance and opinions improve day-by-day. Performance plateaued on day four of the study (analysed using Helmert contrasts). In a follow on study [202], the authors compare the Whistling User Interface U3I and the Vocal Joystick VJ. The Vocal Joystick

allows a user to move the cursor by making vowel sounds via a microphone, speed is proportional to loudness. Clicking is performed by making a short sound. The design is similar to the above with the inclusion of the extra modality (U3I, VJ) and distances (350, 700). Helmert contrasts showed that the day effect was not significant after day 4 for U3I and not significant at all for the VJ. The authors found that U3I performed better than the VJ for mouse clicks, had a lower error rate and was less fatiguing. However, users performed better using VJ on the other performance measures. Like the previous study, user opinions regarding the input techniques improved daily and users' performance with both systems was similar towards the end of the study.

Harada et al., [197] present findings of a longitudinal study conducted to reveal the learning curve of the Vocal Joystick, a voice-based user interface control system. The authors recruited a total of nine participants, five had motor impairments and four had no motor impairments. The study was 10 sessions (at least 3 hours and no more than 48 hours between sessions) with each session lasting for one hour, the first and last sessions lasted for 90 minutes. Participants undertook selection (distance: 150, 280 pixels, width: 30, 80 pixels, angles: 0, 45, 90, 135 degrees) and steering tasks (tunnel radius: 100, 200 pixels, tunnel width: 100, 140 pixels). Improvement of at least 20% was evident over the 10 session period. The group with no motor impairments reached a previously measured expert performance by the end of the 10 session period, while the group with motor impairments reached 70% of that level.

2.4.5 Percentage Preferred Walking Speed (PPWS)

When walking normally, people tend to default to a preferred walking speed [203]. The introduction of a secondary task (for example, reading a text message on a phone) while walking may cause a user to adjust her walking speed accordingly. The effect of the mobile interaction on a user's preferred walking speed is measured as a percentage of the user's default preferred walking speed. The greater the impact the interaction has on a user's default walking speed (for example, causing them to slow down while in use), the less usable while mobile. Percentage Preferred Walking Speed (PPWS) is a measure used to evaluate the impact that mobile interaction has on preferred walking speed [204]. The difficulty of interacting with mobile devices while walking is well documented [118-120]. Mobile interaction (whether that be a technique or a specific input modality or device,

etc) that allows users to walk at their preferred walking speed is therefore seen to be a measure of its effectiveness [203].

Along with other measures, Petrie et al. [203] use the time taken to walk the route, the errors made during the walking task and PPWS to evaluate a wearable outdoor navigational aid for blind travellers. Of the three measures mentioned, they found significant differences in PPWS which provided insights into the effectiveness of the navigation aid. Pirhonen et al. [205], Brewster et al. [204] and Lumsden and Brewster [206] also found PPWS to be a useful measure of mobile usability. In light of these findings, Percentage Preferred Walking Speed (PPWS) [203] is measured in order to assess the impact and suitability of the four pointing devices (studied in this dissertation) on the participants while walking. PPWS which is close to the normal walking speed of the participant demonstrates that the pointing device may be more suitable for use when interacting with a wearable computer while mobile. That is, the device does not impede the performance of the primary task which is interacting with the wearable computer while walking. To this end, it is recognized that PPWS is an interesting characterization of the walking condition and may provide valuable insights into the usability of an input device within a wearable context while mobile.

Brewster et al. [204] and Lumsden and Brewster [206] use PPWS to determine whether the two eyes-free interaction techniques they present for use with a wearable device have an effect on walking speed. The wearable system is made up of a Xybernaut MA V running windows XP placed on the user's belt, a PDA (Compaq iPAQ) connected to the wearable computer, and a pair of headphones used for the audio output. The authors explore interaction techniques that do not require a visual display but rely on audio instruction and feedback. The two techniques comprise of a 3D audio radial pie menu using head gestures in order to select menu items and a 2D gesture recognition system performed with a finger on the screen of a PDA. The authors report significant results for PPWS in the head gesture experiment. In the head gesture experiment, sounds that remained at a fixed position to the user's head requiring the user to simply nod at the appropriate menu selection had less impact on walking speed than the other designs presented. In this condition, participants walked slower at 69% of their normal walking speed, in contrast to 47.5% and 48.5% for the other experimental conditions. Walking speed was slower while using head gestures than when using hand gestures. While

undertaking the hand gesture tasks, participants walked with speeds ranging from 94.7% to 32.8% of their preferred walking speed. Although this was slower than their preferred walking speed, this finding was not significant.

Petrie et al. [203] use PPWS in order to evaluate a wearable outdoor navigational aid for blind travellers called MoODS. The authors identify the importance of evaluating wearables under different types of use, for example, serial use, where by the user performs one task only at a time versus concurrent use, where by the user performs two tasks simultaneously, i.e. walking while selecting items on the screen. Of significance, the authors found that 4 out of 6 participants (one set of data could not be analyzed) achieved closer to preferred walking speed with MoODS than without MoODS.

Pirhonen et al. [205] examine gesture and non-speech audio as a way to control a mobile music player and reduce the need to visualize the interface. The device was a Compaq iPAQ. The gestures were controlled with a finger; the gestures used were, sweep across the screen (left/right) to change between previous and next tracks, sweep down/up the screen to increase/decrease volume and single tap to toggle between start and stop. Audio was provided as feedback from an interaction so that the state of the device may be communicated to the user. Along with other measures, PPWS was recorded in order to measure the effect of the device on participants walking speed. Both interfaces significantly affected PPWS. Participants walked closer to their normal preferred walking speed when using the TouchPlayer than when using the MediaPlayer. The authors [205] found PPWS to be a useful measure of mobile usability. The audio/gestural interface was found to be significantly better than the standard interface.

More recently, PPWS has also been used in the evaluation of scrolling techniques on mobile touch devices [207, 208].

Although Mizobuchi et al. [209] do not use PPWS as a measure, they examine the relationship between walking speed and text input task difficulty. The authors explore the effect key size has on text entry using a PDA handheld device while walking and standing. Participants were asked to enter sentences using an on screen keyboard while walking and standing. The individual keyboard keys were 2 mm, 2.5 mm, 3 mm and 5 mm in size. Text input speed was faster when standing than when walking. The authors found that although participants slowed down considerably while entering text, the

amount they slowed down was not affected by key size. Instead, the authors noticed that the participants would slow down their walking to a fixed pace that allowed them to share their attention between entering text via the PDA and walking. Interestingly, the authors do not appear to measure the participants' preferred walking speed as a basis for comparison. The mean walking speed was 1.77 km/h.

Oulasvirta et al. [121] observed that one of the strategies undertaken while interacting in mobile situations was to either slow down or stop the task that was deemed less important, i.e. participants slowed down their walking in order to interact with a mobile device. The cognitively costly nature [121] of mobile interaction affects not only the secondary task being undertaken (i.e. walking), but also slows, stops or postpones interaction with a mobile device. The authors [121] found that while participants were walking at normal speed, interaction with the device was stopped for a mean of 11.12s and stopped for an average of 5.97s when the participants slowed down their walking.

Yatani and Truong [210] also measure the walking speed of participants while comparing their two-handed software keyboard design to three other stylus-based text entry techniques. Participants were asked to input text while walking along a designated path. The authors noticed that participants walked slower while entering text at an average of approximately 1.9 km/h in contrast to their normal walking speed of approximately 3.8 km/h. The walking speeds are extracted from a graph as the authors do not provide exact numerical values for walking speeds.

Schildbach and Rukzio [118] found that users slow down their walking speed when performing target selection and reading tasks on a touch-screen mobile phone. The authors found that on average participants decreased their walking speed by approximately 25% of their normal walking speed (4.26 km/h) when using a mobile phone for target selection. Similar to Mizobuchi et al. [209], the authors [118] found that there was no effect of target size on walking speed. When reading passages of text, participants slowed their walking speed by more than 1 km/h on average compared to when no mobile device was used. Text sizes did not significantly affect walking speed.

Participants were found to slow down while walking while undertaking visual search [211] and reading tasks [212] on a mobile device. Vadas et al. [212] evaluate reading performance on a handheld visual display and a speech-synthesis audio display while

walking and stationary. Of significance, participants walked faster at 1.20 m/s in the natural (baseline) walking condition, followed by a walking speed of 1.03 m/s for the audio condition and walked the slowest at 0.91 m/s in the visual condition. All differences were significant.

In a similar vein, researchers have also explored the effects of controlling the walking speed of participants has on mobile interaction performance [120, 122, 213].

2.5 Evaluation of Wearable Input Devices

Usability studies investigating input devices for traditional desktop computing environments have a long rich history; however, investigating the performance of input devices for wearable computers is a relatively new field of investigation. Despite the importance of input devices for wearable computing, there has been very little quantitative and qualitative evidence on the usability of such devices [9, 10]. An overview of these investigations into input devices for wearable computers is presented in this section. This section is constrained to the presentation of usability studies pertaining to input devices predominantly used for general-purpose interaction in a wearable context. Of particular relevance to this dissertation is the literature that investigates the usability of pointing devices for wearable computers.

2.5.1 Pointing Device User Studies

A review of wearable literature reveals that there have been a limited number of empirical studies dedicated exclusively to investigating the usability of pointing devices for wearable computers. Section 2.3.1 presented novel devices by which to perform command entry and cursor control in a wearable system using specialised hardware and/or software. Typically, the usability of those novel devices was evaluated via formal or informal user evaluations and in some cases the devices were also compared against commercially available devices. In addition to the description of the novel devices, section 2.3.1 also presented the results of their evaluation where reported by the researchers. The studies presented in this section however describe the research undertaken that focuses on the evaluation of commercial pointing devices for use with wearable computers.

Chamberlain and Kalawsky [10] identify the scarcity of empirical research undertaken on pointing systems for use with wearable computers and the lack of statistical evidence that can support designers and users choice of input device. The authors assert that there is a need for empirical research into both the input modalities for wearable computers and their relation to generic tasks such as target selection and dragging and dropping. To this end, their research evaluates participants performing selection tasks with two pointing systems while wearing a wearable computer. Twenty participants were required to undertake the selection tasks while standing and walking. The authors' [10] study consisted of a 2 by 2 mixed design, where the independent variables were mobility (standing and walking) and input devices (touch screen with stylus and off-table mouse) and the dependent variables measured were time to point, error rate (target misses) and the workload rating (measured via the NASA-TLX). Participants were required to don a wearable computer system (Xybernaut MA IV) housed in a vest with a fold down touch screen and had a five minute training session to familiarise themselves with the input devices. The selection task consisted of five target sizes (radii of 10, 20, 30, 40 and 50 pixels) which appeared on the screen one at a time. One thousand targets were selected (IBM's IDTest version 23 software used) in total comprising of 500 selected while stationary and 500 selected while walking. Participants were required to walk around six cones placed at one metre intervals apart in a figure eight motion. Interestingly, the authors have chosen to evaluate two different interaction methods, where by the stylus does not have an onscreen cursor however, the off-table mouse has an onscreen cursor. In light of this, the results are not surprising. The authors conclude that the stylus was the fastest device (918.3 ms faster in the standing condition and 963.7 ms faster in the walking condition) and had the lowest cognitive workload. The mouse took 145.9 ms longer to use while walking and the stylus took 101 ms longer to use however, these findings are not statistically significant. The off-table mouse reported the lower error rate (the stylus resulting in 24.2 and 19.7 more errors in the standing and walking conditions respectively). Interestingly, the off-table mouse produced fewer errors in the walking condition than the standing condition. Although workload rating values are not specified by the authors, they do state that there was a significantly higher overall workload for the off-table mouse. The physical, temporal, effort and performance sub-scales were significantly different. Participants were observed slowing down in order to select the targets and navigate around the cones in the walking condition. The off-table mouse

used in the study appears to be the same design as the trackball used in the studies undertaken as part of this dissertation. Participants did not wear a head-worn display but were evaluated while wearing a wearable computer and while stationary and walking. Chamberlain and Kalawsky [10] reason that Fitts' law is not a suitable tool to evaluate and assess wearable pointing devices as the targets the user selects may not be stationary given the mobile nature of the user and display which may move with the user's movement. Interestingly, the authors do not provide any qualitative results pertaining to the use of the devices other than the NASA-TLX workload rating and as previously stated, do not provide the actual workload values.

Witt and Kluge [9] evaluated three wearable input devices used to perform menu selection tasks in aircraft maintenance. The study evaluated both domain experts and laymen performing short and long menu navigation tasks. The input devices consisted of a pointing device (handheld trackball), a data glove for gesture recognition and speech recognition. For short menu navigation tasks; laymen performed fastest with the trackball, followed by speech then data glove (statistical difference between the trackball and data glove only). Domain experts performed comparably faster with the trackball and data glove, followed by speech (however, no significant differences were found across the three devices). For long menu navigation tasks, both laymen and domain experts performed faster with the trackball, followed by the data glove, then speech (however no significant difference for laymen was found; no significant difference between trackball and data glove was found for domain experts). The trackball mouse outperformed the other devices. However, qualitative data indicated that domain experts preferred the hands-free nature of the data glove. Speech interaction was found to be difficult by domain experts who exhibited a wide range of language abilities.

2.5.1.1 Series of Pointing Device Evaluations

In a series of studies, Chamberlain [214] evaluated wearable input devices for text entry and pointing while standing and walking. Of relevance to this dissertation are the studies undertaken evaluating three pointing devices, an off-table mouse, a track-pad and a stylus, performing target selection, drag and drop and trajectory based tasks. The off-table mouse and track-pad devices used in the study appear to be the same design as those used in the studies undertaken as part of this dissertation. It is not clear from the

description provided by Chamberlain [214], where on the body the track-pad was placed, whether it was held in the hand, and whether the participants used one or two hands in order to interact with the device. In contrast to the work undertaken as part of this dissertation; in the studies undertaken by Chamberlain [214], participants did not wear a head-worn display instead used a vest mounted fold down touch screen positioned in the middle of the torso just above the hip. The studies employed a between-subject design meaning that participants were assigned to one input device group only. Interestingly, other than the NASA-TLX workload rating, the authors do not provide any qualitative results pertaining to the use of the devices. The three studies consisted of a 2 by 3 mixed design, where the independent variables were mobility (standing and walking) and input devices (Xybernaut stylus, track-pad and off-table mouse) and the dependent variables measured were task time, error rate (target misses) and the workload rating (measured via the NASA-TLX). Participants were required to don a wearable computer system (Xybernaut MA IV) housed in a vest with a fold down touch screen and had a short training session to familiarise themselves with the devices and task. For the walking condition participants were required to walk around six road cones positioned at one metre intervals.

For the target selection task, a significant difference was found between all three devices for total task time and error. The stylus was the fastest device, followed by the track-pad, then the off-table mouse for both the standing and walking conditions. The off-table mouse performed with the least errors, followed by the stylus, then track-pad for both mobility conditions. Chamberlain [214] found a significant difference for workload except between the off-table mouse and track-pad. For the standing condition the stylus (24.1, SD 8.9) had the lightest workload rating, followed by the track-pad (46.8, SD 13.9), then the off-table mouse (47.2, SD 6.2). For the walking condition, the stylus (33.1, SD 11.3) had the lightest workload rating, followed by the off-table mouse (49.5, SD 9.2), then the track-pad (65.4, SD 13.2).

For the drag and drop task, a significant difference found between stylus and off-table mouse only for total task time. For both mobility conditions, the stylus performed with the fastest time, followed by the track-pad, then the off-table mouse. A significant difference was found between the stylus and off-table mouse, and stylus and track-pad for errors. The stylus performed with fewer errors in both mobility conditions, this was

followed by the off-table mouse, then the track-pad for the standing condition. However, the track-pad performed with fewer errors than the off-table mouse for the walking condition. The stylus had the lightest workload rating for both the walking (32.4, SD 8.19) and standing (28.4, SD 18.00) mobility conditions. Chamberlain [214] found a significant difference of workload between the stylus and the off-table mouse and track-pad devices which performed comparably. The off-table mouse produced a workload rating of 64.5 (SD 10.39) for the standing condition and 68.6 (SD 15.24) for the walking condition. The track-pad measuring 64.7 (SD 6.91) while standing and 67.9 (SD 16.67) while walking.

For the trajectory based input task, a significant difference was found between all of the devices for task time and errors. For both mobility conditions, the stylus performed the fastest and with the fewest errors, followed by the track-pad, then the off-table mouse. A significant difference was found between the stylus and off-table mouse and stylus and track-pad. Workload for the standing condition was found to be as follows; Stylus 30.5 (SD 9.395), Track-pad 63.6 (SD 9.155), Off-table mouse 69.7 (SD 17.204). Workload for the walking condition was found to be as follows; Stylus 44.6 (SD 12.020), Track-pad 66.6 (SD 11.177), Off-table mouse 71.4 (SD 10.782).

2.5.2 Interaction Technique User Studies

Researchers have explored techniques to improve selection in a wearable context. Wither and Höllerer [215] evaluate four techniques for positioning a virtual 3D cursor in order to annotate objects in an augmented reality environment. The four approaches which are based on wearable technology include; a Twiddler2 keyboard (T1), a RocketMouse finger trackball (T2), head orientation and two RocketMouse buttons (T3) and head orientation alone (plus a button to toggle between modes) (T4). A user study was conducted which focused on evaluating the four input approaches using wearable technology in order to determine the best controls for positioning a 3D cursor. Thirteen participants were required to navigate a 3D cursor through a slalom course. Participants were explained how an interaction technique worked, followed by a practice session and were then tested on it twice. The participants used a Sony Glasstron PLM-S700E head-worn display with an InterSence Intertrax2 orientation tracker and a Point Gray Firefly camera mounted to it. The study was conducted in virtual reality using a black backdrop in an attempt to avoid the distracting effects of augmented reality backgrounds. The

study aimed to determine the best input techniques for quickly positioning a 3D cursor at a distance. Results of the study showed that the trackball (T2) and head orientation and two buttons (T3) were similarly fast and both were faster than the Twiddler2 keyboard (T1) and head orientation alone (T4) with no significant difference between the trackball (T2) and head orientation and two buttons (T3) and Twiddler2 keyboard (T1) and head orientation alone (T4). Results also showed that the techniques worked comparably well for gates that were at the beginning, middle and end of the courses suggesting that the techniques worked well for large and small distances. Accuracy was measured by the distance the cursor travelled and the number of gates the user missed for the courses. For both measures of accuracy, the techniques were placed in the following order; Twiddler2 keyboard (T1) performed with shorter path distance and fewer gates missed, followed by the trackball (T2), head orientation and two buttons (T3) and lastly head orientation alone (T4). Qualitative results showed that the participants preferred the trackball (T2). The RocketMouse is the same design as the handheld trackball used in this dissertation. Their results indicated that the finger trackball and head orientation with two buttons performed similarly. Both were reported to be considerably faster than the Twiddler2 and head orientation alone with one button. Users preferred the finger trackball.

Lehikoinen and Röykkee [150] present a 1D selection technique for selecting 2D objects in head-worn displays. The 1D selection technique when compared to 2D traditional selection was slower in both stationary and walking conditions. The 1D selection technique while walking is 1.3 times slower than the desktop condition, however, the 2D selection technique is almost twice as long as the desktop condition while walking. The authors use a finger mouse to perform both 1D and 2D selection techniques. For the walking condition participants donned a Plug-N-Run module by Cell Computing and a Sony Glasstron PLM-S700E see through head-worn display. A laptop was used for the stationary condition. Although no metrics are reported to support the testing of the 1D interface, Davis [216] states that users preference is for a 1D pointing scheme while walking however wanted 2D interaction once they became stationary.

Research conducted by Hong et al. [217] explored the use of dynamic cursor gain control in an attempt to improve the performance of pointing devices for use with wearable computers. Dynamic cursor gain control is used to reduce the speed of the cursor's

movement when the cursor is positioned over a target. Eighteen participants participated in a 2 × 2 mixed factorial design. The independent variables were, dynamic gain control and normal gain control, desktop condition (sitting in front of a monitor using a standard mouse) and wearable (Micro-Optical head-worn display using a Dolphin Mouse trackball). Participants were required to perform selection tasks with square targets with a width of 8, 16 and 24 pixels, distances of 200, 300 and 400 pixels, and angles of 10 to -10 degrees. Participants underwent a practice session before the main session. Results indicate that the difference between gain conditions was significant. Average movement time for normal gain control was 2.104 sec where dynamic gain control was 1.918 sec. The authors used Fitts' law to determine the index of performance. In the wearable condition, the dynamic gain condition reports 2.22 bps, whereas the normal gain condition reports 1.59 bps. Desktop condition reports 5.88 bps and dynamic gain conditions improves by 0.66 bps. Results indicate that dynamic gain control improves the selection of targets. Throughput is calculated using the reciprocal of the slope of the regression line ($1/b$) instead of the mean of means as recommended by Soukoreff and MacKenzie [13] and adhering to the ISO 9241-9 standard [11].

2.5.3 Placement of Input Device User Studies

Thomas et al. [151, 152] conducted a study (presented in 1999) exploring the placement of an input device on different positions on a user's body, while the users assumed four postures of sitting, standing, kneeling and prone. The input device was the Easy Cat Touchpad mouse used to operate a wearable computer. The study evaluated the effect of the placement of a Touchpad mouse on a user's body and aimed to determine whether there was any difference when the following factors are varied - the position of the Touchpad on the user's body (forearm, upper arm, torso, thigh front, thigh outer side) and the posture of the user (standing, sitting, kneeling, prone). The study measured time and number of errors when completing selection tasks of circular targets. The wearable computer comprised of a Toshiba Portable Personal Computer 320 Series laptop computer (stored along with the power converters in a small backpack), Sony Glasstron see-through 800 x 600 SVGA display, and the Touchpad mouse. The user study [152] involved 25 participants. Participants underwent a training session and were required to return for a second session which lasted one and a half hours. The touchpad mouse was attached to a desk during the training sessions. Participants were required to use the

Touchpad mouse to select a target placed in the centre of the screen. Once the target had been selected, the target is removed from the screen and a second target is placed offset of 183 pixels in one of eight directions, equally spaced around the centre of the screen. The targets were circles of 40 pixels in diameter. Participants performed 40 tasks in random order for each trial, that is, the eight target positions presented five separate times. Participants performed the tasks in 27 different combinations made up of four postures and seven different placements. The authors [152] found that there were similar time effects for sitting, standing and kneeling. Three groupings of results are seen for mouse position and orientation. The front of the thigh is the best position for the mouse, the forearm, side of thigh and upper arm towards the user's hand are the next grouping. The mouse positions that were seen to be least favourable were the torso (both mouse orientations), and the upper arm with mouse buttons in the up direction. Combining the posturing and mouse position conditions, the results indicate that thigh front mouse position would be most appropriate for sitting, kneeling and standing postures, and the forearm mouse position is to be used for the prone position. The authors note that in the case where one mouse position is to be used for all for postures, the forearm position would be the best choice. Qualitative results indicate participants preferred the forearm placement.

Ashbrook et al. [65] investigated placement (on the wrist, in the pocket and holstered on the hip) and mobility (standing and walking) on the time required to access an interface worn on the body. Not surprisingly, the wrist provided the fastest access time. It was found that placing the device in a pocket or holster incurs a large time penalty of up to 78% of access time.

2.5.4 Longitudinal Text Entry User Studies

While many longitudinal studies have been undertaken evaluating input devices in traditional environments, there are only a handful of longitudinal studies that evaluate input devices for wearable computers. With the exception of Hwang et al. [140] and Horie et al. [142] described earlier (in section 2.3.1), the wearable literature appears to be limited to the longitudinal evaluation of input devices performing text entry or examining text entry techniques only.

An early study (presented in 1997) evaluating input devices for text entry to be used with a wearable computer was undertaken by Thomas et al. [218]. Three input devices, a virtual keyboard, forearm keyboard and a Kordic keypad were evaluated for efficiency and usability. The study aimed to determine for each input device, the training effort required in order to become proficient, the speed at which alphanumeric textual data can be entered, and the number of errors made while entering the data. The messages participants were required to enter were between 10 to 15 English words in length (50 – 65 characters) and contained numeric data. The speed of text entry and the number of errors were recorded. The wearable computer system the authors used was built using off the shelf products and comprised of the Pheonix 2 computer and a headset with earphone, microphone, and Private Eye display. The computer was designed to be worn on a belt. Text entry was performed with the three input devices as follows:

- The forearm keyboard used had standard QWERTY layout and was strapped to participants non-preferred forearm using Velcro straps. Buttons were pressed with the participants' dominant hand.
- The Kordic keypad (Australian Institute of Marine Science – AIMS) was hand sized with five buttons that are used to enter the chords.
- The virtual keyboard involved the use of the ClickPad program (displaying a QWERTY keyboard on the screen) and the use of a belt mounted mouse (comprising an isometric joystick mounted on top of the battery pack attached to the belt and two buttons one in front of the joystick and one behind). The mouse is operated using either the thumb or a finger.

Twelve participants took part in the study. The entire experiment consisted of an initial interview, a training session and the task sessions. The task sessions comprised of six sessions each lasting one hour over a three week period. In each session, participants performed nine text entry tasks (three tasks for each of the three input devices) and one text entry task with a standard keyboard. The participants were required to stand while performing the tasks and walked between stations, described by the authors as indicative of normal wearable use. The stations explained the task and the device to use in order to complete the text entry task. There were three different types of tasks; the open and shut task required participants to start an application, enter a single character and close the application, the message 1 task required participants to start an application, enter a

text message and close the application, the message 2 task was a repeat of the message 1 task undertaken with the same input device. The open and shut task was designed in order to measure the time it took to operate a stopwatch and change focus back to the editor. The start, stop and elapsed times along with the textual information entered by the participant were recorded for each task. Start and stop times were recorded when the participant pressed the start and stop on the stopwatch and the textual data was saved when the participant closed the application. The authors found that the forearm keyboard was the fastest device over the three tasks and six tests, performed with less participant variability, reported less ongoing training effect, and reported performance stability (identified in the trade-off between the time taken for each character and the number of errors per character). Performance stability indicates that a gain in time does not result in an increase in the number of errors. The authors found significant training effects on time occurred for message 1 and message 2 tasks over the six tests indicating that given six hours of exposure, participants quickly learnt to use the devices and rapidly improved in performance. The authors found that for message 1 and message 2 tasks that there was a significant difference between devices in the time taken per character and significant difference between devices in the number of errors per 100 characters. Both speed and error analysis indicated significant differences in the efficiency of the devices. The devices were ranked as follows; forearm keyboard, virtual keyboard followed by Kordic keypad.

Lyons et al. [219] presented a longitudinal study to evaluate the performance and learnability of the Twiddler for text entry tasks. Ten novice participants were presented with two conditions: multi-tap and chording text entry techniques over 20 sessions. Sessions were separated by at least two hours and by no more than two days. Each session lasted approximately 45 minutes and consisted of two parts, 20 mins typing with the multi-tap technique and 20 mins with the chording technique. Each half-session began with a warm-up round consisting of typing two phrases. Warm up data was not used in measuring performance. Participants were required to complete as many blocks as possible within the 20 minute time frame, each block contained 10 text phrases. Participants sat at a computer while undertaking the test. A standard QWERTY keyboard was used during the first and last sessions (two blocks consisting of 40 phrases) to ascertain a baseline typing rate for each participant. The authors found that while users initially had a faster average typing rate with multi-tap, after four sessions, the

differences become insignificant. By the eighth session, participants type faster chording than with the multi-tap. By session 20, participants reach 26.2 wpm and 19.8 wpm with chording and multi-tap respectively. Chording typing rates do not level off, increasing steadily, while the multi-tap speeds begin to plateau.

Building upon their earlier work comparing multi-tap text entry with chording text entry using the Twiddler [219], Lyons et al. [220] explore expert chording. Five participants were recruited from the authors' earlier study [219] and underwent an additional 20 sessions (40 in total including the previous study). By session 40, participants achieved an average typing rate of 37.3 wpm. Once the authors were confident that the participants were considered to be expert users, the participants were asked to continue with two extra phases in order to analyse aspects of expert typing. The additional studies looked at multi-character chording and limited visual feedback. In addition, the data captured from the study allowed the authors to explore how participants learned to type with chords. Results of the study revealed that an average typing rate of 47 wpm was reached. Higher typing rates appear to be achievable with multi-character chords [220]. The experimental design to evaluate blind typing consisted of the following three conditions; normal feedback, dots feedback and blind over 5 sessions of typing where each condition lasted 15 minutes. The normal feedback condition allowed the user to see the text being typed under the phrase given to the participant. The dots feedback presented dots in place of characters, while the blind condition did not show any on-screen feedback. Given the results of the blind typing study, the authors [220] state that the Twiddler can be used effectively with limited visual feedback since the limited feedback did not hinder the participants performance. The authors [220] conclude that text entry via chord typing for use with mobile devices appears to be a viable technique. Although not explicitly stated, this appears to be a stationary experiment similar in nature to the authors' previous work [219].

Clarkson et al. [221] present a longitudinal study (similar in design to Lyons et al. [219] work) of mini-QWERTY keyboard use. The study examines the learning rates of novice QWERTY users and consists of 20 sessions lasting twenty minutes each. Participants were considered novice if they had not used a mini-QWERTY keyboard more than once. The two mini-QWERTY keyboards used in the experiment (Dell and Targus) were connected to a standard computer. The twenty sessions were completed in pairs with a 5 minute break

in between sessions (sessions were separated by at least two hours and by no more than two days). Results indicated that the Targus which averaged typing speeds of 61.44 wpm was significantly faster than the Dell which averaged speeds of 58.61 wpm. The mean desktop typing speeds were also collected. Participants achieved 98.31 wpm (Targus group) and 86.7 wpm (Dell group) with a standard keyboard. Not surprisingly, typing speeds improved over time. For the standard keyboard condition, this may be explained by the participants gaining familiarity with the testing environment. This trend has been reported by other researchers [219].

Clawson et al. [222] examine blind typing on mini-QWERTY keyboards. The authors, stating that attention afforded to the computer is somewhat reduced in a mobile environment, identify the need to be able to enter text rapidly and accurately with limited visual feedback. The study builds on the authors' previous study of evaluating typing rates on mini-QWERTY keyboards described in the preceding paragraph [221]. Eight participants were recruited from their previous study now considered expert mini-QWERTY typists (having completed 600 minutes of training). The study was a 3 × 5 within subjects factorial design, where the three conditions (normal, blind and double blind) were presented to participants over five sessions lasting approximately 75 minutes each (three twenty minute typing conditions including five minute breaks between sessions; sessions were separated by at least two hours and by no more than two days). The authors used the same two keyboards used in their previous study on desktop computers. In the normal condition, the participants had full visual access to both the keyboard and the display. In the blind condition, the participant was not able to see the keyboard, while in the double blind, the participant was not able to see the keyboard and had reduced feedback from the display. Results of the study show that participants reached rates of 45.8 wpm across the blind conditions and 57.04 wpm for the normal condition. Accuracy across the blind conditions was 85.6% while the normal condition was 93.6%. The authors [222] found that the blind conditions reduce typing rate and accuracy. Although rates do improve with practice, they do not reach the rates reported in the normal condition. This contrasts the findings of their previous work on the Twiddler [220], where blind typing did not reduce the users' performance. The authors [222] state that although an advantage of a QWERTY keyboard is they are fast to learn (assuming the user is already familiar with a desktop QWERTY keyboard), they are less advantageous when required for blind text entry. The authors [222] conclude that learning time, the

necessity of blind typing, typing rates and accuracy should be considered when selecting a keyboard for use in mobile or wearable computer situations.

More recently, Bajer et al. [87] evaluate H4-TEG, their glove based design allowing users to enter text by pinching the thumb and fingers together. Six participants were presented with text entry tasks over eleven one hour sessions scheduled over two to three weeks (sessions were separated by at least one hour and by no more than three days, maximum two sessions per day). Participants sat in front of a laptop in order to undertake the tests. The authors report text entry speeds of 14.0 wpm after 9 sessions of practice with mean error rates less than 1%.

It is interesting to note that although the above studies evaluate wearable input device usage over time and produce significant and valuable findings, they do not appear to be indicative of normal wearable operation, that is, the participants were not required to don a wearable computer and all tasks were performed while sitting at a desktop or laptop computer (with the exception of Thomas et al. [218]). The large number of sessions seems fitting as the longitudinal studies explore text entry which one would expect to require a suitable amount of time to learn.

2.6 Limited Wearable Commercial Input Device Evaluation Studies

Despite the availability of pointing devices in the marketplace suitable for use with wearable computers, there is very little published data on user performance with these devices. Table 2 provides a summary of the wearable input device studies presented in this chapter (refer to Appendix A for full table). Studies are positioned in the table according to whether the studies evaluated solely commercial input devices (commercial), evaluated novel input devices (research) or evaluated novel devices against commercially available devices (commercial + research). Studies are also positioned according to the type of display used, monocular head-worn display, binocular head-worn display, a vest worn fold-down screen, PC/laptop monitor or other/not specified displays. Of the research presented, only eight usability studies required the participant to don a wearable computer indicative of wearable use (denoted in the table by the black and italic text). The remaining studies either did not evaluate the participants while wearing a computer and/or it was not explicitly stated (denoted in the table by the blue text). Of the limited research reporting results evaluating participants while wearing a computer,

two published studies evaluate users while wearing a binocular head-worn display (Thomas et al. [151, 152] and Lehikoinen and Röykkee [150]). Although the work undertaken by Chamberlain and Kalawsky [10] and Calvo et al. [143] evaluate users while wearing a computer and performing target selection tasks, the display used is a vest worn fold down screen positioned in the middle of the torso, just above the hip. Likewise the series of studies evaluating target selection, drag and drop and trajectory based tasks undertaken by Chamberlain [214] employs a vest worn fold down screen for the display. Participants in the studies performed by Thomas et al. [218] and Witt and Kluge [9] are evaluated with wearing a monocular head-worn display and evaluate text entry and menu interaction respectively. Although a binocular head-worn display along with a computer is worn by participants in the following studies; Thomas et al. [151, 152] evaluate suitable device placement and Lehikoinen and Röykkee [150] investigate a novel selection interaction technique. Ashbrook et al. [65] investigated the time required to access an interface worn on the body and used a mobile phone in their evaluation. As evidenced, there exists a gap in the literature evaluating commercial pointing devices suitable for use with wearable computers where participants are evaluated while wearing a computer and a head-worn display.

Interest in input devices and interaction techniques suitable for use with head-worn displays is growing as evidenced by the following researchers who have designed input devices with the intention of being used with a head-worn display; uTrack [4] is a 3D input system that can be used for pointing, FingerPad [6] is a nail mounted device that allows the index finger to behave as a touchpad, PACMAN UI [1] is a vision-based input interface also designed to be used as an input technique suitable for use with a head-worn display. Interestingly, both uTrack [4] and FingerPad [6] were evaluated using a laptop/monitor display. The PACMAN UI [1] appears to have been evaluated while participants wore a head-worn display however, the participants did not wear a computer and the posture/mobility of the participants is not specified. With the release of wearable glasses-based displays that are smaller, less obtrusive and targeted towards the consumer market, research into suitable, subtle and socially acceptable interaction with head-worn displays is vital. Although not exploring pointing per se, Lucero et al. [2] and Serrano et al. [7] investigate interaction with glasses and are evidence of the growing interest in and the necessity to understand appropriate input devices and interaction with glasses/head-worn displays.

Table 2: Wearable Input Device Usability Studies. The text in black and italic font denotes a wearable experiment where the user wears the computer on their body. The blue text denotes that the evaluation was not wearable and/or the authors did not specify whether participants donned a wearable computer. Refer to Appendix A for a full table including results

Wearable Input Device Usability Studies					
Device	**Display**				
	Monocular head-worn display	**Binocular head-worn display**	**Fold-down screen (worn on body)**	**PC/Laptop Monitor**	**Other/Not specified**
Commercial	*Thomas et al. (1997, text entry, standing) [218]*	*Thomas et al. (1997, 2002, target selection device placement, sitting, standing, kneeling and prone longitudinal 6 sessions) [151, 152]*	*Chamberlain and Kalawsky (2004, target selection, standing and walking) [10]* *Chamberlain (2004, PhD Thesis, text entry, target selection, drag and drop, trajectory based input, standing and walking) [214]*	Lyons et al. (2004, text entry interaction technique, sitting, longitudinal 20 sessions) [219] Lyons et al. (2004, text entry, sitting, longitudinal 20+5 sessions) [220] Clarkson et al. (2005, text entry, sitting, longitudinal 20 sessions) [221] Clawson et al. (2005, text entry, sitting, longitudinal 5 sessions) [222]	Davis (2001, target selection) [216].
Commercial + Research	Hong et al. (2005, +monitor, target selection interaction technique, sitting) [217] *Witt and Kluge (2008, menu selection, standing) [9]* Horie et al. (2012, target selection, sitting and standing, longitudinal 7 sessions) [142]	*Lehikoinen and Röykkee (2003, +monitor, object selection interaction technique, walking and sitting) [150]* Wither and Höllerer (2004, 3D cursor positioning interaction technique) [215] Kato and Yanagihara (2013, target selection) [1]	*Calvo et al. (2012, target selection, standing) [143]*	Tokoro et al. (2009, target selection) [3]	Rosenberg (1998, target selection) [138] Kim et al. (2005, target selection) [88] Hwang et al. (2005, target selection, menu selection, map nav., text entry, longitudinal 5 sessions) [140]
Research				Oakley et al. (2008, target selection, standing) [5] Bajer et al. (2012, text entry, sitting, longitudinal 11 sessions) [87] Chen et al. (2013, cursor control, sitting) [4] Chan et al. (2013, target selection, sitting and walking) [6]	*Ashbrook et al. (2008, mobile phone touchscreen, accessing device and responding to alerts, standing and walking) [65]*

2.7 Conclusion

This chapter presented relevant knowledge in the following areas; described a wearable computer and the ideal characteristics of a wearable system, provided exemplars of wearable computers, explored input modalities for use with wearable computing, described the methods used to evaluate the usability of pointing devices and presented relevant studies pertaining to the evaluation of wearable input devices.

Given that wearable computing is a relatively new discipline, there does not yet exist a standardised way of interacting with a wearable computer in contrast to desktop computers where a keyboard and mouse are the standard devices. Effective input devices and interaction techniques are essential to the usability of a wearable computing system. Significant advancements have been made in the many aspects of wearable computing [26], however, input techniques continue to be a key challenge [4]. Although much research has been undertaken in wearable interaction, it remains an open problem that is vital to wearable computing. This challenge is well noted in literature [4, 19, 61].

Without access to specialized software or hardware, wearable systems may make use of commercially available products such as Microsoft Windows, existing applications and input devices. To this end, the requirements for textual and command entry remain the same as a desktop system where this is typically performed by the keyboard and mouse respectively. In light of this, users instead need to make use of commercially available input devices that can be used without having to be constructed or having to install specialised software. The input devices must be suitable for use with wearable computers and provide general-purpose input. Pointing is fundamental to most human-computer interactions [2, 5] and is a fundamental operation undertaken in current graphical user interfaces [160, 161]. A mechanism for continuous pointing suitable for use with wearable computing is vital [4, 5] as various forms of wearable computing are adopted.

Despite the availability of pointing devices in the marketplace suitable for use with wearable computers and the need to better understand wearable interaction, there is very little published data evaluating these devices. As evidenced in this chapter, there exists a gap in the literature evaluating commercial pointing devices suitable for use with wearable computers where participants are evaluated while wearing a computer and a head-worn display. Although it may be found that optimal interaction methods for wearable computers may differ from those used in desktop computers, it is important to evaluate the currently available input devices, not only as a means to empirically determine their usability within a wearable context and inform and guide users of the technology when deciding amongst devices, but to also provide a basis on which to inform and guide design so that usable and effective input devices irrespective of interaction metaphor can be created. These first hand observations can also provide a

comparative basis for novel and innovative input methods emerging from research laboratories.

In light of the above, it is therefore critical that wearable human-computer interaction is explored. The following four chapters present the results of a series of studies undertaken that evaluate commercially available pointing devices for use with wearable computers. The studies that follow are motivated by the need to address the existing gap in knowledge.

3

Target Selection User Study

3.1 Introduction

This chapter presents the first study in the series of studies that evaluates the commercially available pointing devices performing target selection tasks. Effective input devices and interaction techniques are essential to the usability of a wearable computing system. Many of the traditional input devices (such as a mouse, keyboard, and joystick) cannot be used effectively in a wearable scenario, as these devices require a level, flat surface to operate. A new form of pointing device is therefore required. Many wearable computing prototypes employ their own particular input mechanisms or adopt variations of well-known input paradigms prevalent in desk-based computer interaction. Without access to specialized software or hardware, wearable systems may make use of commercially available products such as Microsoft Windows, existing applications and input devices. In light of this, the requirements for textual and command entry remain the same as a desktop system where this is typically performed by the keyboard and mouse respectively.

Pointing is fundamental to most human-computer interactions [2, 5] and is a fundamental operation undertaken in current graphical user interfaces [160, 161]. A mechanism for continuous pointing suitable for use with wearable computing is vital [4, 5] as various forms of wearable computing are adopted. The prolific use of Graphical User Interfaces and the WIMP metaphor found on desktop computers typically requires the use of a pointing device in order to interact with the system. Users who wish to run their desktop applications on their wearable computers [3] will likewise require the use of a suitable pointing device given that the interaction metaphor remains the same. Researchers have explored different means by which to perform command entry and cursor control in a wearable system. Pointing devices better suited for use with wearable computers are emerging from research laboratories and as commercial products. However, as identified in the preceding chapter, there are few empirical studies investigating the usability of pointing devices for wearable computers. Research into input modalities and their relationship to generic tasks such as target selection is necessary in order to support the choice of input device for use with a wearable system [10]. The remainder of the chapter describes the method and results of the study and presents a discussion of the findings.

3.2 Experiment

This user study investigates the usability of commercially available pointing devices suitable for use with wearable computers. The general-purpose task performed by participants was target selection. Three commercial pointing devices were used for the target selection tasks; trackball (Section 2.3.3.1), gyroscopic mouse (Section 2.3.3.3) and Twiddler2 mouse (Section 2.3.3.4). All three devices provide the user with the ability to perform general cursor movement and object selection, and all devices may be used with either the left or right hand. The devices were chosen due to the following reasons; their suitability for use with wearable computers; their use was noted in the wearable research literature; and that they are representative of the commercial devices available for cursor control and command entry. Additionally, the devices provide general-purpose interaction suitable for use with wearable computers and are readily available as commercial, off-the-shelf products.

Early wearable computing users and adopters of the technology [8, 20, 21, 157] typically wore a head-worn display of sorts and in some cases, have been wearing them ever since as part of their everyday use [66, 158]. Head-worn displays offer immediacy [8, 66], that is, information is always available at a glance. Information displayed in a head-worn display is private to the user. Head-worn displays also allow the user to be aware of her surroundings, keeping her head-up so that focus on her primary task can be maintained. Together, these offer compelling reasons for the use of a head-worn display in a wearable system and therefore was naturally chosen as the form factor to display information for the presented user studies. This dissertation explores interactions where the information displayed is fixed to the head-worn display [159] irrespective of the user's position or orientation. How to effectively interact with the information presented via a head-worn display is for the most part, an unsolved problem.

The aim of the study was to determine whether there was a measurable difference to a user operating a wearable computer while standing using the different pointing devices.

The hypotheses of the study were as follows:

- H1: There is a measurable difference in task completion time (speed) when performing selection tasks with the three pointing devices.
- H2: There is a measurable difference in number of errors (accuracy) when performing selection tasks with the three pointing devices.

- H3: The pointing devices can be placed in order (ranked) based on task completion time (speed) and number of errors (accuracy).
- H4: Users have a preference of a pointing device.

3.2.1 Participants

Results were gathered from 30 participants who took part in the experiment. Of these, there were 28 males and 2 female, all right handed. The mean age of the participants was 26.8 years (SD 8.8). The participants were volunteers from computer-literate students and staff at the School of Computer and Information Science, University of South Australia. Participants were required to have no prior experience with the pointing devices, to be able to walk and to have normal corrected vision.

3.2.2 Equipment

The experiment was conducted on a Dell Laptop Computer (Inspiron 8000) running the Microsoft Windows XP operating system. The output device used was an optical see-through head-worn display produced by Sony (Glasstron with resolution 800 × 600 SVGA; FoV 30 degrees (h) x 22.5 degrees (v), 38 degrees diagonal). Three commercial pointing devices were used for the target selection tasks; trackball (Section 2.3.3.1), gyroscopic mouse (Section 2.3.3.3) and Twiddler2 mouse (Section 2.3.3.4). The computer and power converters were stored in a small backpack. Although the display and computer could be operated with battery power, the experiment was performed using an extension cord connected to mains power due to the limited battery life. The use of mains power did not impede the users' ability to freely walk around in the experimental environment.

3.2.3 Software and Selection Task

A custom-built application to present the experimental conditions to the participants was written in Java. The custom-built application coordinated an entire session of eighteen (18) tasks. Each task presented forty (40) circle targets, one at a time, to the participant. In order to begin the task, participants were required to select a target positioned in the centre of the screen. Once the target had been selected, that target was removed from the screen and a second target was placed on the screen with an offset of 180 pixels in one of eight directions (N, S, E, W, NE, SE, NW, SW). The eight target directions were

each presented five times in random order. The targets were circles of 40 pixels in diameter.

The application prompted the user to change pointing devices in one of the two following methods: 1) for training sessions, the name of the pointing device to use appeared on the computer display and 2) for experimental sessions, the number of a paper poster for the participant to walk to appeared on the computer display.

3.2.3.1 Data Collection

The data recorded for each trial included the times in nanoseconds at which the user selected or missed the start target and every target selection up to and including the final target. Also recorded was the total number of errors (missed target selections) and the total time taken between the first target selection and the final target selection of each task (40 trials).

3.2.4 Design

The following independent variables (factors and levels) examined were:

Factor	Levels
Device	Trackball mouse, Gyroscopic mouse, Twiddler2 mouse
Block	1, 2, 3, 4, 5, 6

The dependent measures were as follows:

Dependent Measures	Explanation
Task time	The total amount of time (seconds) from the first target selected up to and including the final target selected in a task (i.e. the time taken to select 40 targets).
Number of errors	The total number of missed target selections in a task (40 targets).

The experiment was a $3\ (device) \times 6\ (block)$ repeated measures design, meaning all participants were tested on all levels. To reduce learning effect, each participant performed six blocks of trials presented in random order. For each block participants completed one task (of 40 target selections) with each of the devices, that is, three tasks per block. The devices were presented in random order.

Table 3: Explanation of Terms

Group	Six blocks (presented in random order).
Block	Three tasks (one per pointing device assigned in random order).
Task	40 target selections (in random order – eight directions presented five times).

As outlined in Table 3, one task is defined as forty (40) selections of a target with one pointing device. The 40 target selections in random order were made up of eight target direction positions presented five separate times (8 × 5 = 40 target selections). One block is made up of three tasks, and each task within a block was completed with a different pointing device in a random order. One group is made up of six blocks presented in a random order. A group represented an entire training or experimental session for a participant, with the constraint that there was an equal number of participants who operated each pointing device as the first device of a session. This task was modelled on the previously mentioned point and select studies [151, 163]. However, the position of the targets appeared randomly around the entire screen. The participant's task was designed to emulate a user selecting an icon or graphical object.

3.2.5 Procedure

Participants were required to attend two separate sessions, an initial training session in order to become familiar with the devices and following that, an experimental session.

3.2.5.1 Training Session (Session 1)

During the training session, participants were required to read an information sheet, fill out a consent form, and undergo training using the three pointing devices. The supervisor demonstrated how each of the pointing devices operated prior to the participants having to use them to complete the training task. Participants were instructed to use the devices with their dominant hand. Having understood the operation of the devices, the participants were then asked to start the session, and the supervisor started the custom-built application. The application provided prompts that instructed the participant which pointing device to use in order to complete each task (40 target selections). As the purpose of the session was to familiarise participants with the pointing devices, the participants did not wear the computer in a backpack and did not wear the head-worn display, but rather sat in a chair using the laptop computer placed on a desk to

perform the training. The total duration of the training session was approximately 30 minutes.

3.2.5.2 Experimental Session (Session 2)

Having completed the training session, participants undertook a second experimental session lasting approximately one hour. A minimum of 24 hours was allowed between the training session and the second experimental session. Reading from a script, the supervisor explained to each participant what was expected of them during the session and reminded them how each pointing device worked. The participants were then asked to start the session, and the supervisor started the custom-built application.

Nine stations were positioned around a large room signalled by paper posters on the wall indicating the station number and the pointing device to use. The application provided prompts that instructed the participant to move to the next indicated station. Once the participant reached a station, the poster provided instructions regarding which pointing device to use in order to complete the task (as seen in Figure 8). This was implemented in order to have the participant interact with the environment and in turn perform a task using a wearable computer. The tasks were completed while standing and while wearing the wearable computer with the head-worn display. Standing is one of the typical movement conditions when interacting with a wearable computer and may be adopted in order to interact with the wearable. The stations were addressed more than once, thus the need for only nine stations instead of 18. Participants were asked to rest for at least one minute after completing two blocks.

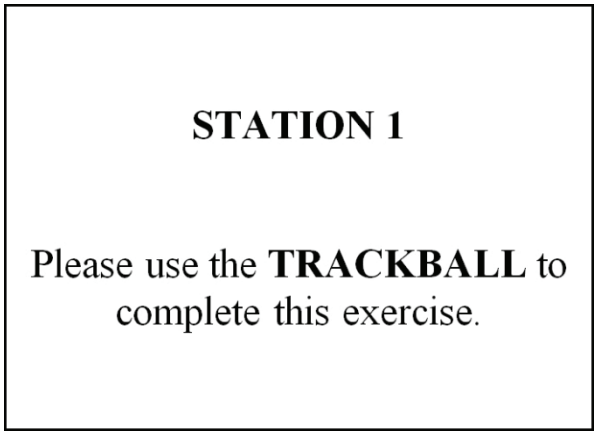


Figure 8: Poster at stations indicating station number and pointing device to use for task

3.3 Quantitative Results

This section reports the results of the usability study undertaken by participants while wearing a computer with a head-worn display and performing general purpose target selection tasks. The empirical results relating to the total task time and the number of errors are presented in this section.

Unless otherwise stated, Analysis of Variance (ANOVA) models are used to determine significance. Mauchly's test was used to determine whether sphericity had been violated. If the assumption of sphericity was violated, degrees of freedom were corrected using Greenhouse-Geisser estimates of sphericity. Statistical significance was set at 0.05. A Bonferroni correction was employed for all post hoc analysis.

3.3.1 Task Time

Across all devices and participants the mean total time for one task was 64.558 seconds (SD 17.071). An ordering effect based on the first pointing device the participant operated in the experiment was tested for. Group 1's first device in the experiment was the trackball, group 2's was the gyroscopic mouse, and group 3's was the Twiddler2. In a single factor ANOVA model which tested the effect of ordering on mean total time, there is a significant effect of group number on mean total time per task $F_{(1.829,327.390)}$ = 5.946, $p <$ 0.05. A learning effect across all devices and participants by block number was tested for; block 1 being the first block. There is a significant effect of block number on mean total time per task $F_{(4.318,384.344)}$ = 6.461, $p < 0.01$ from a single factor ANOVA model. There was a significant individual participant effect on mean total time per $F_{(29,58)}$ = 5.886, $p <$ 0.01. Across all groups, blocks, and participants, there is a significant device effect on mean total time per task $F_{(2,58)}$ = 29.300, $p < 0.01$.

Table 4: Mean time in seconds by group (selection task)

Group	Mean (sec)	Std. dev.	Minimum	Maximum
1	64.830	19.141	33.698	134.146
2	67.114	18.065	41.145	158.366
3	61.729	13.044	38.826	112.468

A significant effect of group number implies an ordering effect regarding the device the participants operated first. Table 4 lists the mean times per task over all participants for

each group. A training effect was observed with a significant effect on block number. Table 5 shows the mean times per task over all participants for each block.

Table 5: Mean time in seconds by block (selection task)

Block	Mean (sec)	Std. dev.	Minimum	Maximum
1	69.583	18.996	40.417	145.054
2	67.585	19.634	34.899	141.744
3	64.988	17.052	38.802	134.146
4	62.397	13.882	33.698	108.035
5	62.502	17.430	34.618	158.366
6	60.292	12.999	37.442	98.080

To better understand this learning effect, Figure 9 depicts a graph illustrating the mean time of a task for each device by group number over the six blocks. The legend codes each data series by a two digit number (group number, device number). The group and device number coding scheme is (1) trackball, (2) gyroscopic mouse, and (3) Twiddler2. Viewing the graph, data series 13, 23, and 33 tend to remain the top three or slowest device (Twiddler2). Where data series 12, 22, and 32 tend to be the fastest device (gyroscopic mouse), and the data series 11, 21, and 31 all tend to be in the middle. While there is a statistically significant effect depending on which device was operated first in the first task of the experiment, there is also a statistically significant effect due to device type.

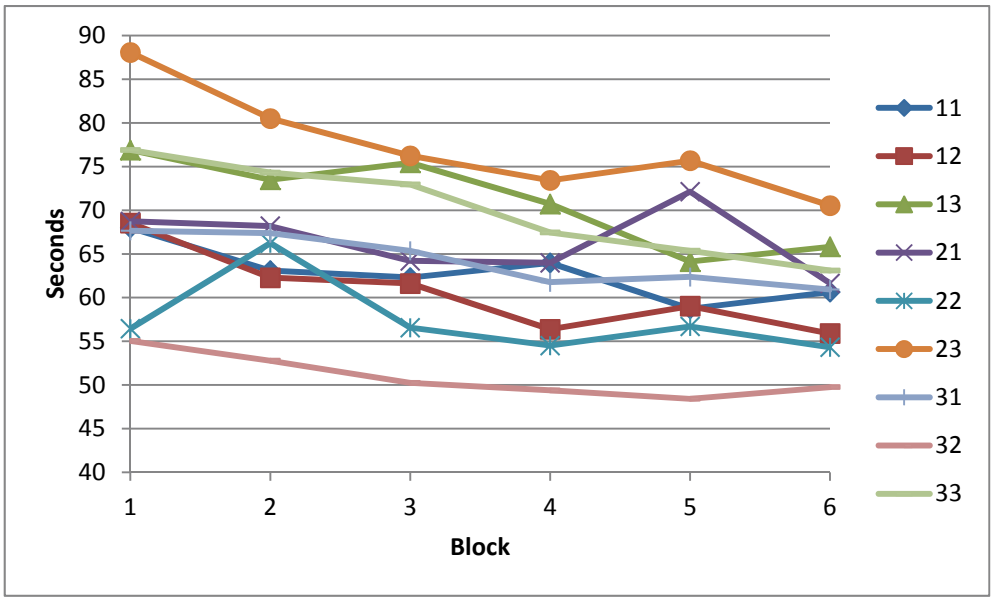


Figure 9: Mean time per task by group and device

Of importance to this study, there was a significant effect of device on mean total time per task. Table 6 lists the mean times per task over all participants for each device. Post hoc testing between all device pairs revealed all the devices were significantly different. The devices can therefore be ordered from fastest to slowest as follows: (1) Gyroscopic mouse, (2) trackball, and (3) Twiddler2. In a multivariate ANOVA model (taking account of random participant effects, block, group and device effects) the pattern of effect remains (significant effects of all independent predictors).

Table 6: Mean time in seconds by pointing device (selection task)

Device	Mean (sec)	Std. dev.	Minimum	Maximum
Gyroscopic	56.338	17.066	33.698	141.744
Trackball	64.501	13.037	45.944	158.366
Twiddler2	72.834	16.719	45.519	145.054

3.3.2 Number of Errors

Across all participants and devices there were 2.6 errors (SD 2.8) per task, with a range of 0–18 errors per task. Overall the number of errors correlated poorly with the total time per task (r2 = 0.0004) or 0.04%.

Univariate ANOVA models revealed the following: there is no significant effect of group number on errors per task $F_{(2,358)} = 1.800$, $p > 0.05$; there is no significant effect of block number on errors per task $F_{(5,445)} = 0.934$, $p > 0.05$; there is a significant effect of participant on errors per task $F_{(29,58)} = 2.664$, $p < 0.01$; and there is a significant effect of device on errors per task $F_{(1.512,43.834)} = 15.225$, $p < 0.01$. Post hoc testing between all device pairs revealed that the gyroscopic mouse and Twiddler2 indicated no significant differences, and that the trackball significantly performed with a lower error rate. Table 7 lists the mean error by pointing device. The trackball pointing device had a lower mean error rate and a lower maximum error rate per task. The Twiddler2 ranked second, with the gyroscopic mouse having the highest error rate.

In a multivariate ANOVA model (taking account of random participant effects, block, group and device effects) the pattern of effect remains (significant effect of device and individual participant), and not of block or group.

Table 7: Mean error by pointing device (selection task)

Device	Mean errors (per task)	Std. dev.	Maximum
Trackball	1.4	1.6	9
Twiddler2 mouse	3.1	2.4	18
Gyroscopic mouse	3.4	2.9	16

3.3.3 Twiddler2 Key Press Study

A key press study was undertaken in order to determine whether the choice of key used to select a target (i.e. perform a left click) influences the performance of the Twiddler2. A study with six participants was carried out to determine whether the use of the 'BS' key instead of the 'A' key to select targets affected the performance of the Twiddler2. The study was similar to that of the training session outlined in section 3.2.5.1. Results of the study show the 'BS' key performed with a lower error rate and a faster completion time than with selection using the 'A' key. A significant effect of key on mean total time to complete one task $F_{(1,5)}$ = 14.848, $p < 0.05$ was found. It is interesting to note that there was no significant effect of key on the mean number of errors per task $F_{(1,5)}$ = 2.250, $p > 0.05$. An exit questionnaire filled out by participants showed that 5 out of 6 participants preferred the 'BS' key over the 'A' key. As indicated by the results, using the "BS" key did not impede the performance of the Twiddler2, rather results indicated that the Twiddler2 performed better using the 'BS' key than the 'A' key for left click.

3.4 Participant Survey and Qualitative Results

Participants completed an exit questionnaire for pointing device satisfaction. Participants were asked to describe their experience using the device, what they liked, disliked and whether they had any difficulties using the device in order to select targets. Participants were also asked to rate the devices on a 7 point scale in terms of overall reaction to the device. Table 8 lists the attributes the participants were asked to rate and scale. The mean rating across all participants and attributes for each of the devices is as follows: gyroscopic mouse 2.67 (SD 1.34), trackball 2.87 (SD 1.43) and Twiddler2 4.63 (SD 1.57). Figure 10 graphs the mean values across all participants for each attribute for each device. The graph shows a preference for the trackball and gyroscopic mouse across all attributes. The graph depicts ease of use, speed of use, accuracy, intuitive, comfort and button press as being

comparable for the trackball and gyroscopic mouse. It is interesting to note that while most of the rating factors are comparable between the two devices, a variation occurs with cursor movement. Participants found that moving the cursor with the gyroscopic mouse easier than with the trackball.

Table 8: Rating factors for pointing devices

Ease of use	(1) very easy	(7) very difficult
Speed of use	(1) too fast	(7) too slow
Accuracy	(1) very precise	(7) very imprecise
Intuitive	(1) very intuitive	(7) very confusing
Comfort	(1) very comfort	(7) very uncomfortable
Cursor movement	(1) very easy	(7) very difficult
Button press	(1) very easy	(7) very difficult

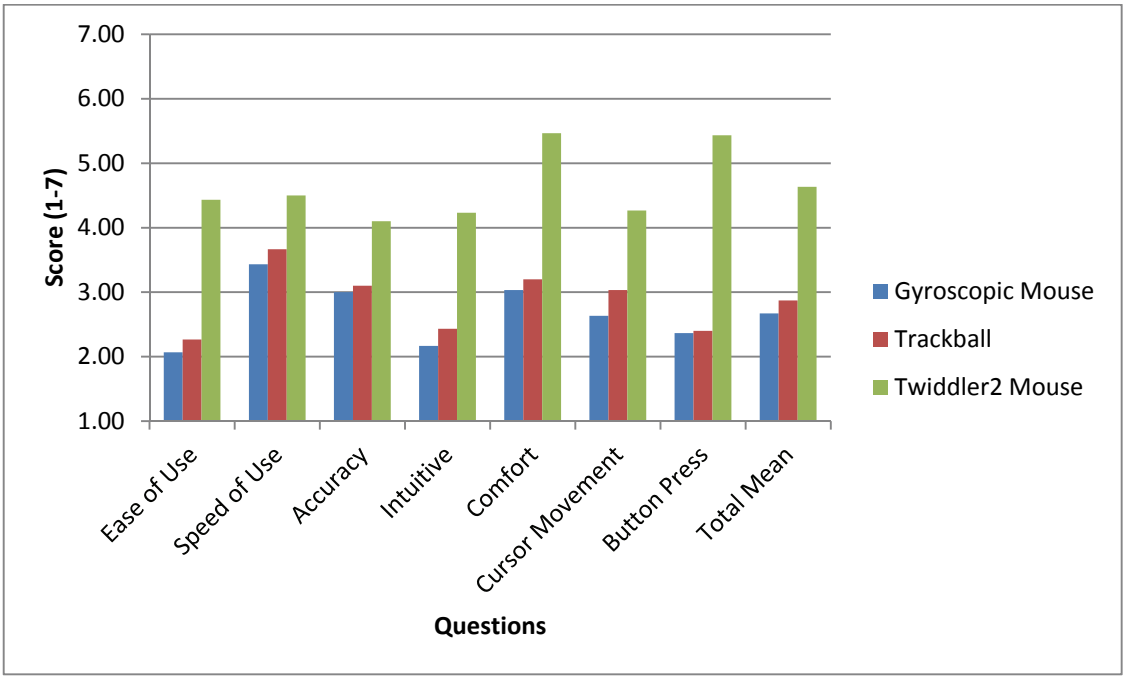


Figure 10: Mean values of rating factors (selection task)

The participants were asked to explicitly rank the three devices in order of 1st, 2nd, and 3rd, as shown in Table 9. The rankings support the survey findings depicted in Figure 10.

Written responses obtained from the survey relating to likes and dislikes of the pointing devices, along with cursor movement and selection difficulties, are discussed in this section. Although the number of comments does not reflect the usability of each device, it does

however provide an insight into the possible methods for improving these devices. The comments were categorized to provide a means of determining overall concerns and positive features. In some instances, participants provided multiple comments when answering a particular question.

Table 9: Participant rankings (selection task)

Rank	Trackball	Gyroscopic	Twiddler2
1	12	17	1
2	14	10	6
3	4	3	23

3.4.1 Trackball

The comments relating to the question "Trackball cursor movement and selecting difficulties" fell into the following three categories; eight comments about the form factor, one comment about the non-intuitiveness and eleven comments about the precision of selection. Having to use the thumb to move the cursor was the a concern. A typical comment being: "*Starting with the thumb in a central position on the ball, most movements seemed to require slightly more than one roll sideways, requiring the thumb to return to the initial position and repeat the movement; this is somewhat tiring for the thumb. Diagonal movement seems somewhat hard to perform compared to horizontal or vertical movement*." The form factor of the device was also identified as a concern. A comment representative of this was: "*You cannot adjust the device to suit your hand. For me, the trackball hole for the pointer finger was too big*".

The comments concerning the "Like about trackball?" fell into the following four categories: fourteen comments about the form factor, seventeen comments about the intuitiveness, two comments about the low level of fatigue, and fourteen comments about the precision of a selection. Participants liked the fact that it appeared to operate similar to a traditional mouse, with comments like: "*Usage similar to a normal mouse and therefore very intuitive, fast to move, relaxing usage - the hand could even hang down*". The design of the device was found to be pleasing, with the following example comment: "*Simple design, easy to hold and use*".

The comments concerning the "Dislike about trackball?" fell into the following three categories: eleven comments about the form factor, two comments about the fatigue using the device and eleven comments about the precision of a selection. A number of comments centred on the difficulty of using the thumb for fine control and the device being hard to hard hold. The following comments were typical of those stated: "*Very sensitive, hard to position accurately. Uncomfortable*", and "*Using my thumb alone made it difficult to move the cursor*".

3.4.2 Gyroscopic Mouse

The comments concerning the "Gyroscopic mouse cursor movement and selecting difficulties" fell into the following four categories: thirteen comments about the device effecting selection, four comments about the form factor, seven comments about the non-intuitiveness and three comments about the precision of a selection. Reported fatigue to the hand and arm produced involuntary hand movements. An example comment being, "*Expected cursor to point where I was aiming, intuitively. Hand started shaking after prolonged use. Hand moves on trigger press*". This is a typical comment about the form factor of the device. "*Always pressing the movement button makes it sometimes complicated if the starting position wasn't the centre. Mouse click with thumb quite uncomfortable*". The precision of the device produced comments like the following: "*Very sensitive and required too much high precision to move cursor to exact spot*".

The comments concerning the "Like about gyroscopic mouse?" fell into the following three categories: thirteen comments about the form factor, nineteen comments about the intuitiveness, and three comments about the precision of a selection. The positive comments centred on the following: easy to use, intuitiveness, the wireless nature, and good form factors. The following comment was representative: "*Easy to hold, no cord, felt very intuitive and easy to click the button without moving it while the gyro on button was still pressed*".

The comments concerning the "Dislike about gyroscopic mouse?" fell into the following four categories: thirteen comments about holding the device effecting selection, four comments about the form factor, seven comments about the non-intuitiveness and three comments about the precision of a selection. Once again the participants noted fatigue to hand and arm, with comments like: "*Take a while to get used to it. Hand is hurting after*

use". The participants reported cursor positioning problems, "*Unsteady cursor movement*". There were a few participants having problems with button configurations, with comments such as: "*Having to remember to hold the "trigger" button to move the cursor, but this stopped being an issue when I got used to it after a while"*.

3.4.3 Twiddler2 Mouse

The comments concerning the "Twiddler2 cursor movement and selecting difficulties" fell into the following three categories: twenty three comments about the form factor, one comment about the non-intuitiveness and nine comments about precision of a selection. The comments manly focused on the positions of the buttons for mouse button presses, difficulty positioning the cursor precisely, and the device (for some) was awkward to hold. The following comments were characteristic: "*Hard to handle because of the position of the fingers and thumb at the back. Hard to reach the button on the front. You have to learn how to handle it*", "*Unable to comfortably hold as it was not flexible to hand size*".

The comments concerning the "Like about Twiddler2 mouse?" fell into the following three categories: seven comments about the form factor, six comments about the intuitiveness, and nine comments about the precision of a selection. Precision of cursor movement and the fact the device is both a cursor control device and keyboard were listed in the positive comments about the Twiddler2 mouse. With the following example comments: "*Cursor movement is extremely easy, even for tiny adjustments. It is the least tiring of the devices for the thumb"* and "*possibility of a whole keyboard*".

The comments relating to the question "Dislike about Twiddler2 mouse?" fell into the following three categories: twenty five comments about the form factor, two comments about the non-intuitiveness and one comment about precision of a selection. Once again the main concern about the device was the shape, placement of buttons, and the method of mouse button presses combined with cursor movement. The following is an example of comments: "*Cursor button is too small. Moving the cursor and pressing the buttons is uncomfortable*".

3.5 Discussion

Results from the study clearly demonstrate that there is a measurable difference in task completion time (supporting hypothesis 1) and number of errors (supporting hypothesis 2) when performing selection tasks with the different devices. There is a significant effect of device on mean total task time and mean error rate across all groups, blocks and participants. The pointing devices can be placed in order based on task completion time and number of errors (supporting hypothesis 3). The gyroscopic mouse performed with the fastest mean time, followed by the trackball, while the Twiddler2 performed with the slowest mean time. The Trackball performed with a lower error rate, followed by the Twiddler2, while the gyroscopic mouse performed with the highest error rate. Survey results show a preference for the gyroscopic mouse and trackball across all attributes over the Twiddler2 mouse. Participants ranked the gyroscopic mouse first, the trackball second and the Twiddler2 third (supporting hypothesis 4).

Although the trackball performed with the lowest error rate and participants found it to be quite comfortable, it was noted that some participants found that the thumb operating on the ball did not offer enough fine grain motor skills. However, leveraging previous skills with a traditional mouse made for a more intuitive device, perhaps being the device of choice for infrequent/novice users of wearable computers.

Participants found the Twiddler2 the least comfortable to use. Some participants expressing that pain occurred in the hand during use. Although ranking third for mean time and second for error rate, participants noted that cursor movement seemed to be easier than the other devices. The Twiddler2 is the only one of these devices that is a combination text entry and cursor control device interface, thus providing a greater level of functionality.

The wireless nature of gyroscopic mouse was favourably commented on, but this feature required it to be self-powered and use a bulky base station. Although the gyroscopic mouse performed with the fastest mean time, it performed with the highest error rate. Perhaps demonstrating that fine grain movement is difficult to perform with the wrist and/or forearm. Fatigue was a problem reported by participants, perhaps providing an insight as to its high error rate. Forcing users to hold their hands and arms in a fixed position and orientation for extended periods of time caused fatigue and produced

involuntary hand movements that affected the cursor position and selection. Perhaps the gyroscopic mouse may therefore only be used for small, short tasks, or where the user is able to rest between tasks.

3.6 Conclusion

This chapter presented a usability study that compared three commercially available pointing devices (a trackball, a gyroscopic mouse and Twiddler2 mouse) performing cursor movement and selection tasks for use with wearable computers. The gyroscopic mouse performed with the fastest mean time. The trackball ranked second, with the Twiddler2 having the slowest mean time performing selection tasks. Testing indicated that the trackball performed with a significantly lower error rate. The Twiddler2 ranked second, with the gyroscopic mouse having the highest error rate. However, post hoc testing between gyroscopic mouse and Twiddler2 indicated no significant differences. The qualitative results obtained by means of a survey, support the ranking based on time and clearly show a preference for the gyroscopic mouse and trackball across all attributes over the Twiddler2 mouse. Participants ranked the gyroscopic mouse first, the trackball second and the Twiddler2 third. The majority of comments made by the participants indicated that a number of attributes influenced their use of a handheld pointing device. The form factor of the device in terms of accommodating hands of differing sizes and comfort was noted. The placement of mouse buttons was identified as an important consideration.

Of interest is whether certain devices are better suited to certain tasks or whether there is an optimal pointing device in terms of operator performance over a suite of tasks. The next chapter builds upon this work and evaluates the pointing devices when performing drag and drop tasks.

4

Drag and Drop User Study

4.1 Introduction

The previous chapter presented a usability study that compared three commercially available pointing devices performing target selection tasks. The study identified that the gyroscopic mouse performed with the fastest mean time, followed by the trackball, with the Twiddler2 performing the slowest. Testing indicated that the trackball performed with a lower error rate, the Twiddler2 ranked second, with the gyroscopic mouse having the highest error rate (however, no significant difference was found between the gyroscopic mouse and Twiddler2 pair). The qualitative results obtained by means of survey support the ranking based on time. Participants ranked the gyroscopic mouse first, the trackball second and the Twiddler2 third.

Although interaction models for wearable computers may differ from those used in desktop computers, it is important to explore all possible pointing interaction models in a wearable context. The studies presented in this chapter extend the selection study by evaluating the pointing devices when performing an increasingly complex task, drag and drop. Performing a drag and drop operation requires the user to press the button on the pointing device in order to select a target, move the cursor (while keeping the button pressed, that is, drag the target) and release the button once the object is repositioned on the destination target. The complexity of the first study is also extended by the introduction of a walking condition in addition to a stationary condition. The studies presented in this chapter evaluate participants while wearing a computer on their back and using a head-worn display. The remainder of the chapter describes the method and results of the study and presents a discussion of the findings.

4.2 Experiment

The usability studies presented in this chapter investigate the usability of four commercially available pointing devices while stationary and walking. The general-purpose task performed by participants was drag and drop. Three commercial pointing devices evaluated in the previous chapter are used (trackball (Section 2.3.3.1), gyroscopic mouse (Section 2.3.3.3), Twiddler2 mouse (Section 2.3.3.4)), with the addition of the touchpad device (described in Section 2.3.3.2).

The aim of both the stationary and walking experiments was to determine whether there was any measurable difference to a user operating a wearable computer using the different pointing devices.

The hypotheses of the study were as follows:

- H1: There is a measurable difference in task time (speed) when performing drag and drop tasks with the four pointing devices.
- H2: There is a measurable difference in error rate (accuracy) when performing drag and drop tasks with the four pointing devices.
- H3: The pointing devices can be placed in order (ranked) based on task time (speed) and error rate (accuracy).
- H4: The users have a preference for a pointing device.

4.2.1 Participants

Results were gathered from 24 participants who took part in the experiment. Of these, there were 19 males and 5 females; 2 left handed and 22 right handed. The mean age of the participants was 26.96 years (SD 6.52). The participants were volunteers from computer-literate students and staff at the University of South Australia. Participants were required to have no prior experience with the pointing devices in a wearable context, to be able to walk and to have normal corrected vision.



Figure 11: Backpack used in experiment

4.2.2 Equipment

The experiment was conducted on a Toshiba Laptop Computer (Portégé M200) running the Microsoft Windows XP operating system. The output device used was an optical see-through head-worn display produced by Sony (Glasstron with resolution 800 × 600 SVGA; FoV 30 degrees (h) x 22.5 degrees (v), 38 degrees diagonal). Four commercial pointing devices were used: trackball, gyroscopic mouse, Twiddler2 mouse and touchpad. The computer, wireless receiver and power converter were attached to a small backpack (modified baby carrier seen in Figure 11). The display and computer were operated with battery power.

4.2.3 Software and Drag and Drop Task

A custom-built application based on the ISO 9241-9 standard for dragging tests [11] was written in Java. The application was designed to present the experimental conditions to the participants. A screen shot of the application is shown in Figure 12.

Participants were required to sequentially drag and drop a blue target across a circle to destination targets as quickly and accurately as possible. Twelve yellow destination targets were positioned at a given distance, equally around the centre of the screen (indicating all possible target positions). The yellow destination targets were coloured red in turn to indicate the location in which to drop the blue target. A task is started when the participant selects the blue target and ends when the sequence is completed (that is, the participant has moved the blue target onto all of the destination targets until he/she is back at the starting point). The starting point is positioned randomly on one of the 12 destination targets. One task presents a combination of two target distances (300 pixels and 500 pixels) and three target sizes (16 pixels, 32 pixels and 48 pixels). The target sizes were chosen as they represent typical icon sizes used by Microsoft. Each device is tested on all conditions.

4.2.3.1 Data collection

The data recorded for each trial included the times in nanoseconds at which the user attempted to select the start (blue) target and every selection and drop operation, until and including the final drop operation. Also recorded was the total number of errors (missed

target selections and drop locations) and the total time between the first selection and the final drop operation of each task (13 trials).

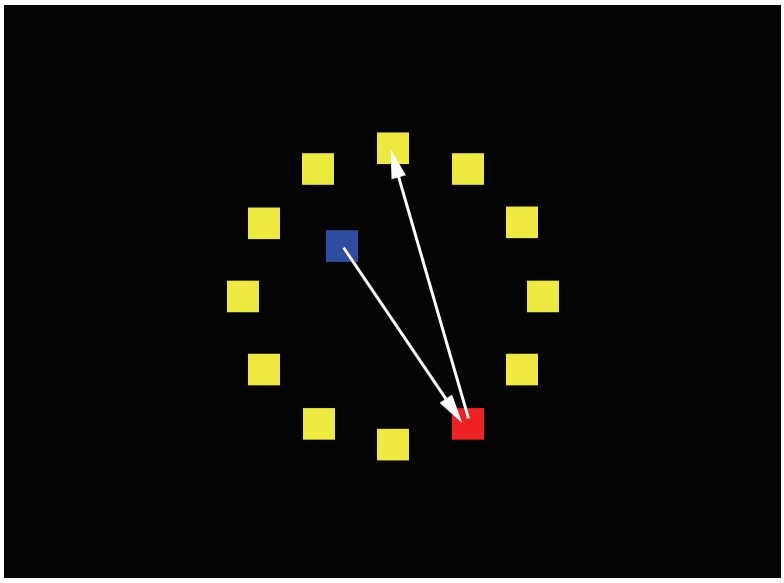


Figure 12: Drag and drop application

4.2.4 Design

This section outlines the design of the standing and walking experiments.

The independent variables (factors and levels) for the stationary usability study were:

Factors	Levels
Device	Trackball, Gyroscopic mouse, Twiddler2 mouse, Touchpad
Block	1, 2, 3, 4, 5, 6
Distance	300 pixels, 500 pixels
Size	16 pixels, 32 pixels, 48 pixels

The independent variables (factors and levels) for the walking usability study were:

Factors	Levels
Device	Trackball, Gyroscopic mouse, Twiddler2 mouse, Touchpad
Block	1, 2
Distance	500 pixels
Size	48 pixels

The dependent variables for both the stationary and walking usability studies were:

Dependent Measures	Explanation
Task time	The total amount of time (seconds) from the first selection up to and including the final drop operation (i.e. the time taken to perform 13 drag and drop operations).
Number of Errors	The total number of missed target selections and missed drop locations in a task (13 trials).

4.2.4.1 Design of Standing Experiment

The experiment was a $4\ (device) \times 6\ (block) \times 2\ (distance) \times 3\ (size)$ repeated measures design, meaning all participants were tested on all levels. The independent variables (factors and levels) are outlined in section 4.2.4 above. To reduce learning effect, each participant performed six blocks of trials presented in random order. Each block consisted of four tasks in random order undertaken with each of the four devices.

Table 10: Explanation of terms (drag and drop task)

Group	Six blocks (presented in random order)
Block	Four tasks (one per pointing device assigned in random order)
Task	13 drag and drop trials (random starting order)

As outlined in Table 10, one task is defined as thirteen drag and drop operations to a destination target with one pointing device. One block is made up of four tasks. Each task within a block used a different pointing device in a random order and a different distance and size combination (presented in random order). One group is made up of six blocks. A group represents an entire training or experimental session for a participant, with the constraint that there was an equal number of participants who operated each pointing device as the first device of a session. This task was modelled on the previously mentioned point and select studies [151, 163] as well as the ISO 9241-9 [11] standard for drag and drop testing. The design of the participant's task was to emulate a user dragging and dropping an icon or graphical object.

4.2.4.2 Design of Walking Experiment

The experiment was a $4\ (device) \times 2\ (block)$ repeated measures design, meaning all participants were tested on all levels. The independent variables (factors and levels) are

outlined in section 4.2.4 above. Each participant performed two blocks of trials presented in random order. Each block consisted of four tasks with each of the four devices presented in random order. Each task within a block used a different pointing device in random order, and a distance of 500 pixels and a target size of 48 pixels. The distance and target size were limited to 500 pixels × 48 pixels due to the mobility of the participants. Likewise, the experiment was constrained to two blocks only due to the mobility of the participants and being mindful of the possible fatigue in which additional tasks may cause. Participants were asked to rest for at least one minute between blocks. The remainder of the design is the same as the stationary experiment's design. The participant's task was designed to emulate a user dragging and dropping an icon or graphical object while walking.

4.2.5 Procedure

Participants were required to attend two separate sessions, an initial training session in order to become familiar with the devices and an experimental session that followed the training session.

4.2.5.1 Training Session (Session one)

The participants were required to undertake an initial training session (duration of approximately 30 minutes), during which they were asked to read an information sheet, fill out a consent form, and undergo training using the four pointing devices. The supervisor demonstrated how each pointing device operated prior to the training. Participants were instructed to use the devices with their dominant hand. The participants were then asked to start the session, and the supervisor started the custom-built application. The application provided prompts that instructed the participant which pointing device to use in order to complete each task (13 trials). As the purpose of the session was to familiarise participants with the pointing devices, the participants sat in a chair using the laptop computer on a desk to perform the training.

4.2.5.2 Experimental Session (Session two)

Having completed the training session, participants undertook a second experimental session lasting approximately one hour. A minimum of 24 hours was allowed between the training session and the second experimental session. Reading from a script, the supervisor

explained to each participant what was expected of them during the session and reminded them how each pointing device worked. The participants were then asked to start the session, and the supervisor started the custom-built application. Session two was divided into two parts; participants were first required to complete the experiment while stationary, and were then required to complete the experiment while walking. Participants were asked to rest for at least one minute after completing two blocks.

Twelve stations were positioned along the walls of a quiet hallway (signalled by paper posters on the wall indicating the station number and the pointing device to use). The application provided prompts which instructed the participant to move to the next indicated station. Once the participant reached a station, the poster provided instructions regarding which pointing device to use in order to complete the task. This was implemented in order to have the participant interact with the environment and in turn perform a task using a wearable computer. If undertaking the stationary experiment, users would remain at the station while they completed their task. If undertaking the walking experiment, users were asked to walk at a normal pace approximately half the length of the corridor and then back repeatedly while completing the task. The stations were addressed more than once.

4.3 Quantitative Results

This section describes the results of the stationary and walking experiments. Unless otherwise stated, Analysis of Variance (ANOVA) models were used to determine significance. Mauchly's test was used to determine whether sphericity had been violated. If the assumption of sphericity was violated, degrees of freedom were corrected using Greenhouse-Geisser estimates of sphericity. Statistical significance was set at 0.05. A Bonferroni correction was employed for all post hoc analysis.

Across all devices, mobility conditions and participants, the mean total task time for one task was 45.259 (SD 30.923) seconds. There is a significant effect of mobility $F_{(1,23)}$ = 45.350, $p < 0.05$ and device $F_{(1.38,31.69)}$ = 29.702, $p < 0.05$ on task completion time. There is also a significant interaction between mobility and device $F_{(1.11,25.51)}$ = 66.078, $p < 0.05$ where the standing position allowed for faster completion times than walking with certain devices.

Across all devices, mobility conditions and participants, the mean total number of errors for one task was 6.068 (SD 10.072). There is a significant effect of mobility $F_{(1,23)}$ = 34.917, $p <$ 0.05 and device $F_{(1.55,35.72)}$ = 19.508, $p < 0.05$ on the mean total number of errors. There is also a significant interaction between mobility and device $F_{(1.28,29.54)}$ = 33.679, $p < 0.05$ where standing was less error prone than walking depending on the device being used.

Table 11: Mean time (seconds) by pointing device (drag and drop task)

Device	Mean (sec)	Std. dev.	Minimum	Maximum
Both mobility conditions				
Trackball	36.83	12.82	16.65	88.73
Touchpad	37.64	16.70	15.35	128.27
Twiddler2	52.43	21.18	15.16	132.00
Gyroscopic	54.14	51.84	15.00	308.92
Standing				
Gyroscopic	32.15	13.19	15.00	93.45
Trackball	36.59	13.33	16.65	88.73
Touchpad	37.49	17.48	15.35	128.27
Twiddler2	53.73	22.54	15.16	132.00
Walking				
Trackball	37.57	11.25	18.44	69.66
Touchpad	38.08	14.27	19.82	86.81
Twiddler2	48.52	16.00	24.37	85.43
Gyroscopic	120.11	66.83	39.84	308.92

4.3.1 Stationary Task Time

Across all devices and participants the mean total time for one task while standing was 39.989 seconds (SD 18.893). Analysis revealed the following:

- There is no effect of group number on mean total time per task $F_{(3,429)}$ = 0.974, $p >$ 0.05.
- There is an effect of block number on mean total time per task $F_{(4.36,413.92)}$ = 3.239, $p <$ 0.05. However post hoc pairwise comparisons report no significant differences.
- There is a significant effect of participant on mean total time per task $F_{(23,69)}$ = 5.064, $p < 0.05$.
- There is a significant effect of device on mean total time per task $F_{(3,69)}$ = 30.020, $p <$ 0.05.

An ordering effect based on the first pointing device the participant operated in the experiment was tested for; no effect of group on task time was found. A learning effect

across all devices and participants by block number was tested for; no effect of block number on task time was found.

Of importance to this study, there was a significant effect of device on mean total time per task. Table 11 lists the mean times per task over all participants for each device and mobility condition. A post hoc analysis was performed between the gyroscopic mouse and trackball, trackball and touchpad and touchpad and Twiddler2. There was a significant effect for all pairs except between the trackball and touchpad devices. The speed of operation for the devices can be placed into the following three groups: the fastest device was the gyroscopic mouse, the trackball and touchpad ranking the second fastest, while the slowest device was the Twiddler2.

4.3.2 Stationary Number of Errors

Across all participants and devices there were 4.24 total errors (SD 5.68) per task while standing, with a range 0 – 40 total errors per task. There is a significant effect of group on total errors $F_{(2.71,387.12)}$ = 4.030, $p < 0.05$ meaning an ordering effect based on the first pointing device the participant operated in the experiment was found. However, there is no effect of block number on total errors $F_{(4.47,424.52)}$ = 0.919, $p > 0.05$ meaning a learning effect across all devices and participants by block number was not found. There was a significant individual participant effect on total errors $F_{(23,69)}$ = 2.292, $p < 0.05$. Across all groups, blocks, and participants, there is a significant device effect on total errors $F_{(3,69)}$ = 3.850, $p < 0.05$.

The total number of errors in a task is made up of missed target selections and missed drop locations. Missed target selections are selections that occur when a target to be selected for a drag operation is missed (that is, the click falls outside of the blue drag target). Targets that are released (dropped) outside of the red destination target are counted as missed drop locations. Qualitative evidence suggests that users found that the trackball was susceptible to dropping the target being dragged and therefore resulting in missed drop location errors. To further understand the source of errors, error analysis is separated into missed target selections and missed drop locations. Table 12 lists the mean missed dropped and target selection errors by device and mobility conditions. The mean missed drop errors were 2.88 errors (SD 4.39) per task. There is a significant device effect on drop miss errors $F_{(3,69)}$ = 3.345, $p < 0.05$. Post hoc analysis

revealed a significant difference between the gyroscopic mouse and trackball. As seen in Table 12, the Twiddler2 and trackball performed comparably with a higher error rate per task than the gyroscopic mouse and touchpad reporting the lower error rates per task. The mean missed target selection errors were 1.36 errors (SD 2.04) per task. There is no significant device effect on missed target selection errors $F_{(3,69)} = 2.007$, $p > 0.05$.

Table 12: Missed target selection errors and missed drop location errors by pointing device (drag and drop task)

	Missed drop error		Missed target error	
Device	**Mean**	**Std. dev.**	**Mean**	**Std. dev.**
Standing				
Gyroscopic	1.61	2.29	1.03	1.39
Touchpad	2.41	3.64	1.19	1.87
Twiddler2	3.52	5.38	1.65	2.42
Trackball	3.97	5.18	1.58	2.28
Walking				
Touchpad	2.33	3.41	0.73	1.43
Twiddler2	3.46	4.36	0.88	1.47
Trackball	7.10	7.52	2.31	2.57
Gyroscopic	13.10	8.27	16.27	17.53

4.3.3 Walking Task Time

Across all devices and participants the mean total time for one task while walking was 61.069 seconds (SD 49.298). Analysis revealed the following: there is no effect of group number on mean total time per task $F_{(2.52,118.22)} = 2.209$, $p > 0.05$; there is no effect of block number on mean total time per task $F_{(1,95)} = 2.505$, $p > 0.05$; there is no effect of participant on mean total time per task $F_{(23,69)} = 1.684$, $p > 0.05$; and there is a significant effect of device on mean total time per task $F_{(1.139,26.200)} = 45.574$, $p < 0.05$.

An ordering effect based on the first pointing device the participant operated in the experiment was not found (that is, no effect of group on time). Across all devices and participants by block number, there is no effect of block number on time indicating that a learning effect was not found. Of importance to this study, there was a significant effect of device on mean total time per task. Table 11 lists the mean times per task over all participants for each device and mobility condition. A post hoc analysis was performed on all pairs of devices. There was a significant effect for all pairs except between the trackball and touchpad devices. The speed of operation of the devices can therefore be placed into

the following three groups: the trackball and touchpad performed with a lower mean time, the Twiddler2 mouse was the next fastest, while the slowest device was the gyroscopic mouse.

4.3.4 Walking Number of Errors

Across all participants and devices there were 11.55 total errors (SD 16.44) per task while walking, with a range 0 – 104 total errors per task. An ordering effect based on the first pointing device encountered in the experiment was tested for and revealed no significant effect of group on errors $F_{(2.14,100.46)}$ = 2.573, $p > 0.05$. There is no effect of block number on total errors $F_{(1,95)}$ = 0.471, $p > 0.05$ indicating a learning effect was not evident. There was no significant individual participant effect on total errors $F_{(23,69)}$ = 1.409, $p > 0.05$. Across all groups, blocks, and participants, there is a significant device effect on mean total errors $F_{(1.327,30.510)}$ = 27.647, $p < 0.05$.

To further understand the source of errors, error analysis is separated into missed target selections and missed drop locations. The mean missed drop errors were 6.5 errors (SD 7.49) per task. There is a significant device effect on missed drop errors $F_{(2.31,53.20)}$ = 21.875, $p < 0.05$. Post hoc analysis revealed a significant difference between all pairs except between the trackball and Twiddler2 and the Twiddler2 and touchpad. The mean missed target selection errors were 5.05 errors (SD 10.99) per task. There is a significant device effect on missed target selection errors $F_{(1.03,23.75)}$ = 18.689, $p < 0.05$. Post hoc analysis reveals a significant effect for all pairs except between the Twiddler2 and touchpad. The devices can be placed into the following three groupings: the touchpad and Twiddler2 performed comparably with the lower error rate, followed by the trackball having the next lowest error rate, while the gyroscopic mouse performed with the highest error rate. Table 12 lists the mean missed dropped and target selection errors by device and mobility conditions.

4.3.5 Target Size and Distance Analysis (standing) – Time and Error

A 4 (device) x 6 (size and distance) ANOVA was conducted on the dependent measure of mean task time. As previously mentioned, device had a significant influence on mean time for drag and drop tasks $F_{(3,69)}$ = 30.020, $p < 0.05$. Overall, the size and distance of the targets had a significant influence on mean time for drag and drop tasks $F_{(3.13,71.93)}$ =

101.186, $p < 0.05$. An interaction between device and size and distance was not found $F_{(6.32,145.38)} = 1.308$, $p > 0.05$. Post hoc analysis on the size and distance of the targets found a significant effect for all pairs except between size and distance combinations of 32x300 and 48x500. Table 13 lists the mean task time for size and distance factors in ascending order of time.

Table 13: Mean size and distance task time (drag and drop task)

Wheel	Mean	Std. dev.	Minimum	Maximum
48 x 300	29.82	13.40	15.00	86.40
48 x 500	34.15	13.44	15.89	77.01
32 x 300	34.26	14.46	16.60	93.11
32 x 500	39.40	16.47	20.43	109.10
16 x 300	47.45	18.79	20.47	98.90
16 x 500	54.84	22.69	27.79	132.00

It is evident that it takes longer to complete a task as the difficulty of the task increases [175], that is either by decreasing the size of the target and/or increasing the distance between the targets. Targets that are larger and are closer together can be selected faster than targets that are smaller and further away from each other. Target sizes of 48 pixels placed at a distance of 300 pixels apart are dragged and dropped significantly faster than any other combination. Figure 13 illustrates the performance of the devices for each of the target size and distance combinations.

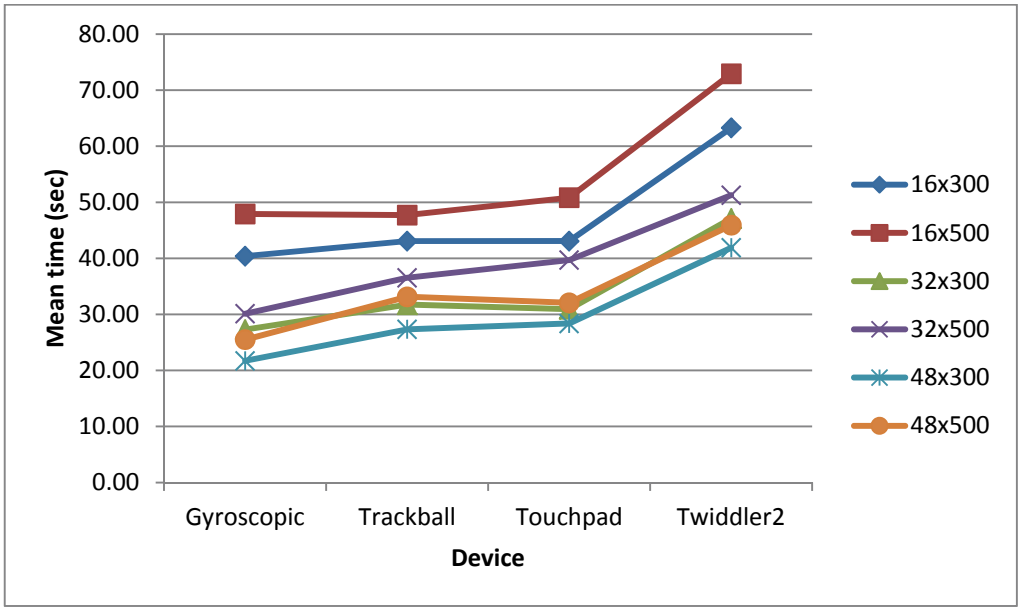


Figure 13: Mean time size and distance by device interaction (drag and drop task)

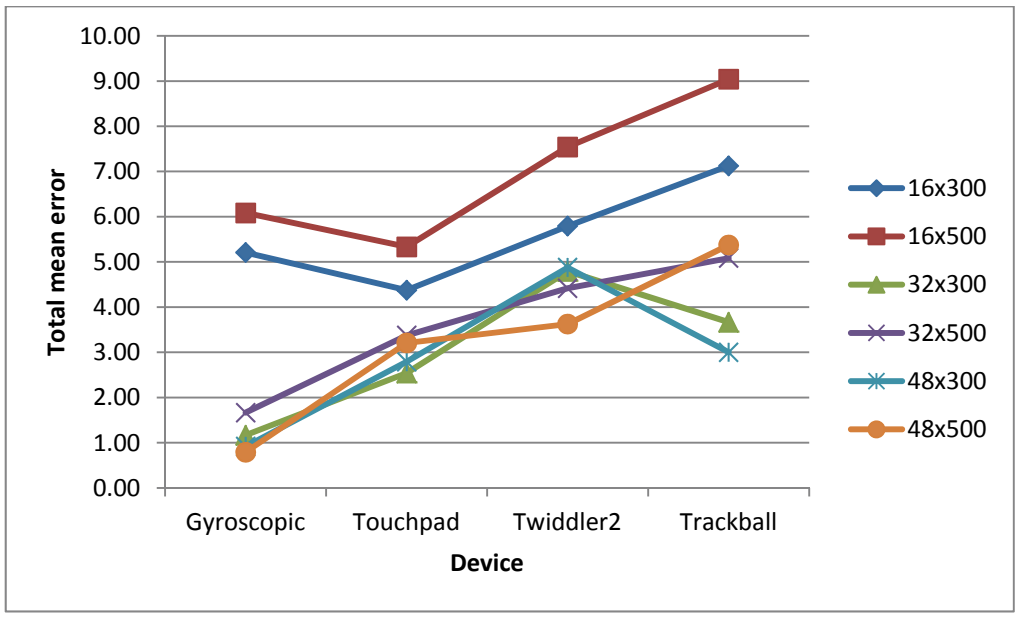


Figure 14: Mean total error size and distance by device interaction (drag and drop task)

A 4 (device) x 6 (size and distance) ANOVA was conducted on the dependent measure of mean number of errors. As previously mentioned, device had a significant influence on total error for drag and drop tasks $F_{(3,69)} = 3.850$, $p < 0.05$. Overall, the size and distance of the targets had a significant influence on mean total error for drag and drop tasks $F_{(5,115)} = 15.883$, $p < 0.05$. An interaction between device and size and distance was not found $F_{(6.26,143.90)} = 1.083$, $p > 0.05$. Post hoc analysis on the size and distance of the targets found a significant effect for the following size and distance combinations: 16x300 and 32x300, 16x300 and 48x300, 16x300 and 48x500, 32x300 and 16x500, 48x300 and 16x500, 16x500 and 32x500, and 16x500 and 48x500.

Table 14: Mean size and distance total error (drag and drop task)

Wheel	Mean	Std. dev.	Minimum	Maximum
48 x 300	2.90	4.85	0	26
32 x 300	3.04	4.84	0	25
48 x 500	3.25	4.76	0	24
32 x 500	3.64	5.16	0	32
16 x 300	5.63	6.31	0	40
16 x 500	7.00	6.68	0	37

Table 14 lists the mean total error for size and distance factors in ascending order of error. It is evident that target sizes of 16 pixels placed at either 300 pixels or 500 pixels apart were more error prone than the other size and distance combinations. Figure 14 illustrates the

mean total errors per task performed by each device for every target size and distance combination.

4.4 Participant Survey

Participants completed an exit survey with seventeen questions rating the use of the devices on a 7 point scale in terms of overall reaction and experience. Surveys were completed for both the stationary and walking experiments. The first eleven questions were concerned with attributes such as smoothness, speed, and accuracy. Figure 15 illustrates the mean across all participants for each attribute for each device while stationary. In general, all devices received a positive response of above a mean of 3.5 (effort, button press, and dragging attributes for the Twiddler2 fell just below, while comfort and ease of use fell just below 3.0). Likewise for the walking condition, devices received a positive response of above a mean of 3.5, with the exception of the gyroscopic mouse and the Twiddler2. The gyroscopic mouse performed well under 3.5 for the attributes of smoothness, effort accuracy, speed, ease of use, cursor movement, and dragging. The Twiddler2 performed just under 3.5 for the attributes of comfort, button press and dragging. Figure 16 illustrates the mean across each attribute for the walking condition.

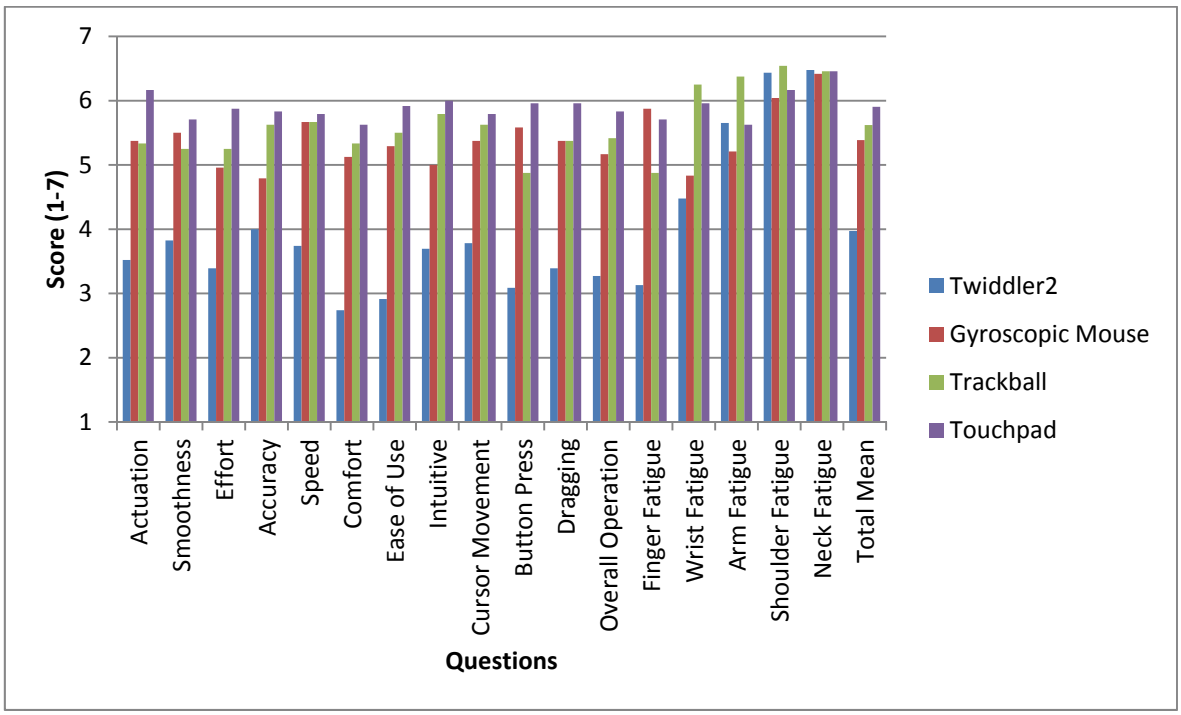


Figure 15: Mean values of rating factors – stationary (drag and drop task)

Participants were asked to rate the "overall operation of device". The mean rating across all participants for "overall operation of device" is as follows for the stationary experiment (scale of 1 very difficult to 7 very easy): touchpad 5.83 (1.27 SD), trackball 5.42 (1.38 SD), gyroscopic mouse 5.17 (1.37 SD) and Twiddler2 3.27 (1.28 SD). The following means were found for the walking experiment: touchpad 5.58 (1.38 SD), trackball 5.35 (0.98 SD), Twiddler2 3.48 (1.27 SD) and gyroscopic mouse 1.60 (1.12 SD). The results representing the standing experiment show a preference for the touchpad with trackball and gyroscopic mouse being comparably ranked second (supporting hypothesis 4). The walking experiment results show a preference for the touchpad and trackball with the Twiddler2 being ranked second and the gyroscopic mouse ranked third (supporting hypothesis 4).

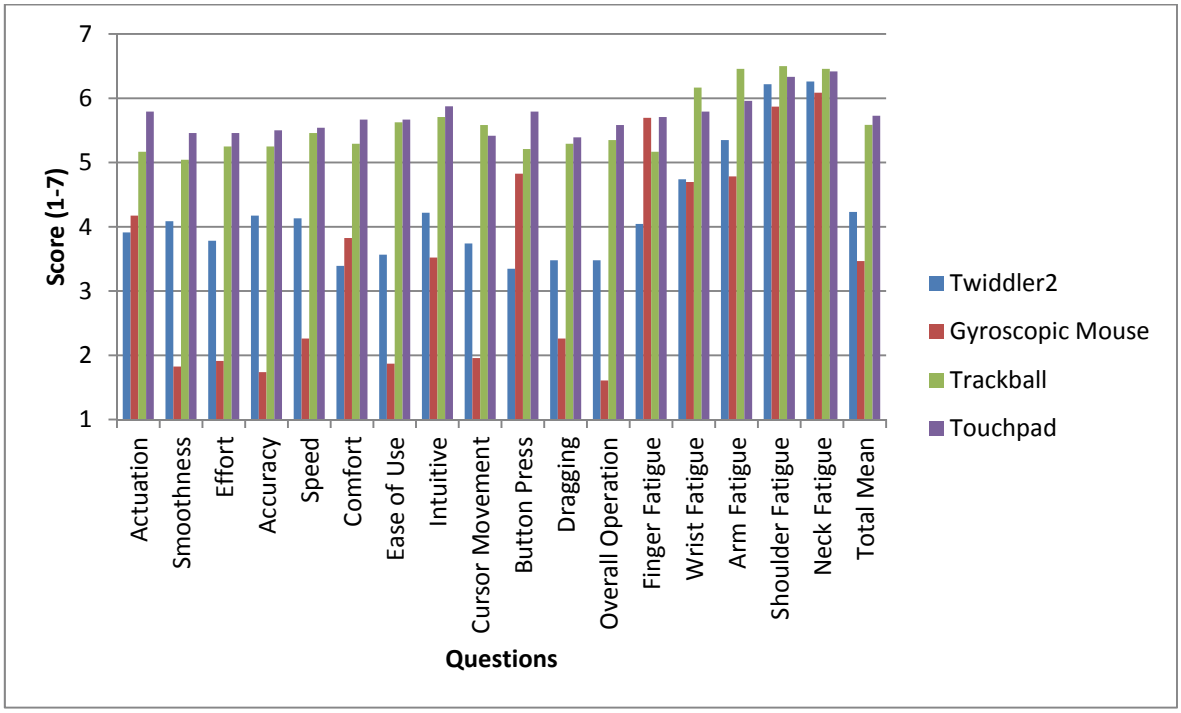


Figure 16: Mean values of rating factors – walking (drag and drop task)

The remaining five questions were concerned with neck, shoulder, arm, wrist and finger fatigue. The reported fatigue was generally low for each of the attributes, with the exception of the Twiddler2 which reported slightly greater finger fatigue. The Twiddler2 and gyroscopic mouse reported slightly greater wrist fatigue. Arm fatigue was also reported by the gyroscopic mouse. However, the trackball mouse reported slightly less arm fatigue.

Table 15: Participant rankings - stationary and walking conditions (drag and drop task)

	Stationary				*Walking*			
Rank	**Trackball**	**Gyroscopic**	**Twiddler2**	**Touchpad**	**Trackball**	**Gyroscopic**	**Twiddler2**	**Touchpad**
1	6	6	0	12	12	0	1	11
2	9	6	1	8	11	0	3	10
3	8	8	6	2	1	1	19	3
4	1	4	17	2	0	23	1	0

The participants were asked to explicitly rank the four devices in order of 1st, 2nd, 3rd and 4th, for both experiments. The frequency of responses presented in Table 15 demonstrates that participants have a preference of pointing devices (supporting hypothesis 4). Twelve participants ranked the touchpad first, six ranked the trackball and the gyroscopic mouse first in the standing condition. For the walking condition, twelve participants ranked the trackball first, eleven ranked the touchpad first and one ranked the Twiddler2 first. Participants deemed that the Twiddler2 while standing and gyroscopic mouse while walking were not worthy of a first place ranking.

4.5 Qualitative Results and Discussion

Results from the study demonstrate that there is a measurable difference in task time (supporting hypothesis 1) and number of errors (supporting hypothesis 2) when performing drag and drop tasks while stationary and while walking. The pointing devices can be ordered based on task completion time and number of errors (supporting hypothesis 3). In the stationary experiment, the gyroscopic mouse performed with the fastest mean task time, the trackball and touchpad ranking the second fastest, the slowest device was the Twiddler2. The gyroscopic and touchpad mouse reported the lower error rate, while the Twiddler2 and trackball reported the higher error rate. In the walking experiment, the trackball and touchpad performed with the fastest mean task time, the Twiddler2 was the next fastest, while the slowest device was the gyroscopic mouse. The Twiddler2 and touchpad devices performed with the lower error rate, the trackball ranking the next lowest, while the gyroscopic mouse reported the highest error rate.

Although performing a drag and drop operation is a more complex task than selection, it is interesting to note that the drag and drop findings correlate to the results of the selection study presented in Chapter 3. When used while stationary, the gyroscopic mouse

performed with the fastest mean time for both selection and drag and drop operations. The gyroscopic mouse also performed with the lowest error rate (when stationary), which differs from the selection study where it was ranked comparably second. The results obtained from the two studies seemingly make the gyroscopic mouse a favourable choice when both interaction models (selection and drag and drop) are required and the user is to remain stationary while using the device. The gyroscopic mouse ranged from the fastest and most accurate device for stationary drag and drop operations, to the slowest and least accurate when performing the same tasks while walking. The performance while walking is not unexpected, as the inertial sensing technology (for example, accelerometer) in the gyroscopic mouse is susceptible to vibration noise. The noise that contributes to the large standard deviation values is perhaps an insight into why participant has no effect on the time and error rate while walking, but is significant when stationary. Some participants were noticed to slow down almost to a stop while attempting the tasks while walking with the gyroscopic mouse. In the drag and drop operations, typically more errors are caused by missing the destination target when releasing the target being dragged (i.e. missed drop locations) over failing to select the target to drag (i.e. missed target selections). Interestingly though, missed target selections is the larger contributor to the overall error count than missed drop locations while walking and using the gyroscopic mouse.

For both selection and drag and drop tasks, the trackball was ranked second for mean time. Interestingly, the trackball performed with the lowest error rate for selection tasks and performed with the highest error rate for drag and drop tasks. A possible reason may be that in order to perform a drag and drop operation, users were required to hold the trigger button while moving the target using the thumb. The form factor was noted on more than one occasion as making this difficult, with the following comment as an example: *"The size of the overall device made pressing the button while moving the cursor slightly difficult. I feel if the device was larger it would be easier to manage".* Although the trackball performed with the fastest mean time while walking, the above problem of holding the trigger button while using the thumb to move a target was reported to worsen while walking. A typical comment was as follows: *"Walking made previous problem (letting go of click) slightly more sensitive".* Other participants however, did not have the same experience while walking with the device: *"Smooth. Pointer stays in place while walking, turning etc. Not affected by walking motion".* The problem of letting go of the

button while dragging using the trackball appears to be exacerbated by longer distances as seen in Figure 14, the distances of 500 pixels for all target sizes reporting higher errors than their 300 pixel counterparts.

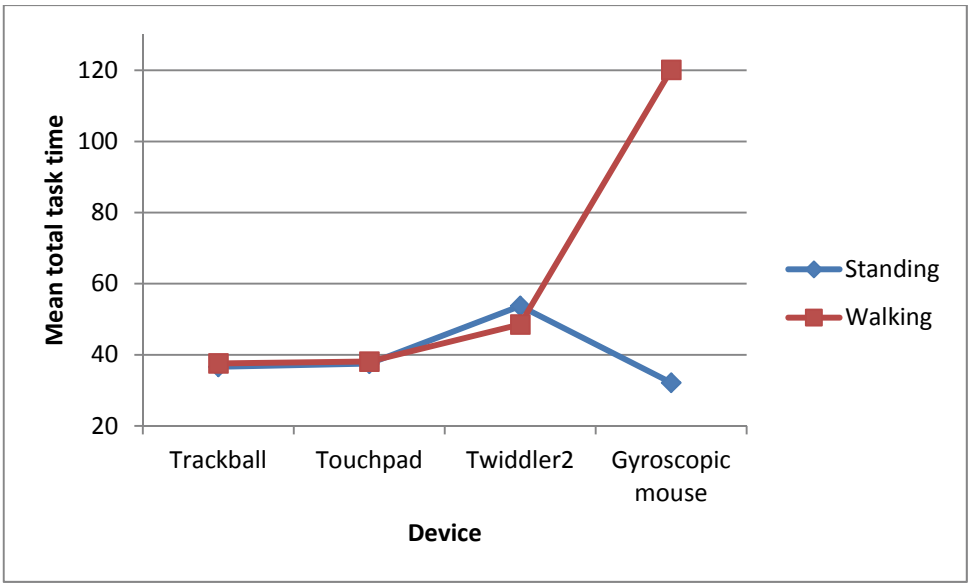


Figure 17: Mean total task time per device for both mobility conditions (drag and drop task)

Figure 17 illustrates the mean total task time for each device and both mobility conditions. The trackball and touchpad performed comparably between the two mobility conditions. Interestingly, a paired-samples t-test revealed that the Twiddler2 performed significantly faster while walking $t(23) = 2.70$, $p = .013$. Understandably, the gyroscopic mouse was significantly slower while walking $t(23) = -7.96$, $p = .000$. The touchpad along with the trackball were shown to have superior performance overall for a device to be employed in both the walking and stationary conditions. These findings perhaps make the trackball or touchpad a favourable choice if both interaction models (selection and drag and drop) are required and it is likely that the user will be moving while using the devices. Some of the comments from participants regarding the touchpad are as follows: *"it was intuitive and not susceptible to movement, making it accurate whilst in motion".* However, other participants noted the following: *"two hands are occupied"* and *"due to moving my arms relative to each other, keeping the button clicked for dragging and keeping the cursor steady was difficult while walking".* A possible advantage of the touchpad over the trackball is the ability to physically place the device in a number of positions on a person's body. In a previous study [151], it was found that the front or outer of the thigh reported one of the fastest mean times and was preferred by users. In

the case where a one handed interaction is required by the user, this would be advantageous as it allows both hands to be free when the device is not in use and the use of only one hand when interacting with the device. Walking with the device secured to the participant's thigh however may cause problems in that the walking motion may affect the drag and drop operation.

The touchpad and Twiddler2 performed comparably between the two mobility conditions for mean total error, however, a paired-samples t-test revealed that both the trackball ($t(23)$ = -2.84, p = .009) and gyroscopic mouse ($t(23)$ = -6.16, p = .000) performed with significantly fewer errors while standing. Interestingly, the total error rate reported for the touchpad was lower for the walking experiment than the stationary experiment (seen in Figure 18). A possible reason may be due to the fact that because some participants found using the device while walking difficult, extra care was taken when selecting and positioning the target, therefore leading to fewer errors. Participants may have also significantly slowed down their walking speed in order to interact with the device. Perhaps further study pertaining to the participants walking speed and the impact on mobile interaction is needed in order to fully understand the use of pointing devices while on the move.

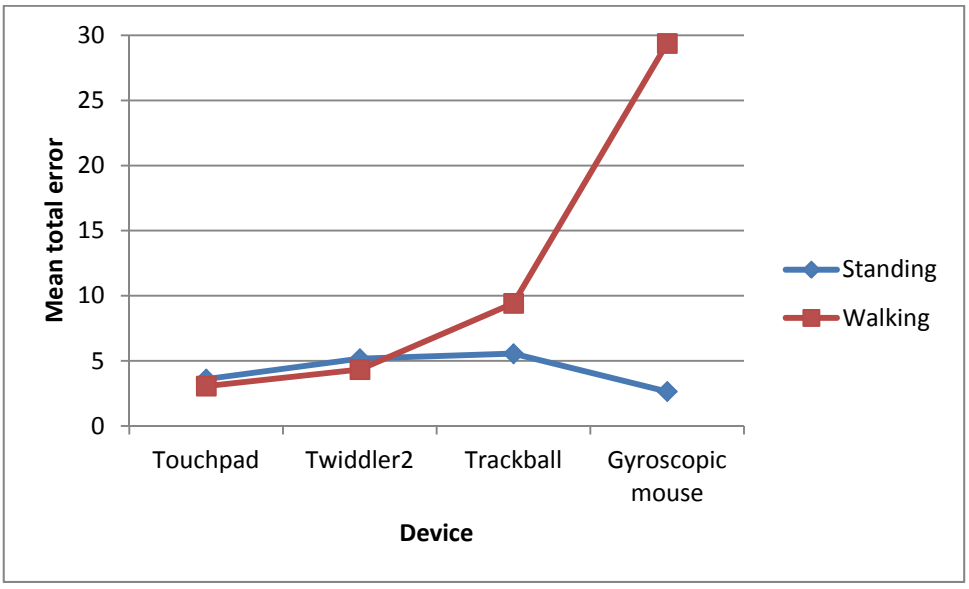


Figure 18: Mean total error per device for both mobility conditions (drag and drop task)

It is interesting to note that the mean times and error rates for the Twiddler2 improved in the walking experiment over the stationary experiment. This may be a result of participants spending more time with an unfamiliar device. Further work needs to be

done on this in order to explore the findings. Some indicative positive comments were as follows: *"The thumb movement is better than the trackball - one gesture as opposed to a couple"* and *"not affected by walking".*

4.6 Conclusion

Usability studies that compared four commercially available pointing devices performing drag and drop tasks for use with wearable computers were presented in this chapter. The first study required the participants to perform tasks while stationary. The second required participants to perform the tasks while walking.

The results pertaining to task completion time indicated that the devices can be placed into the following three groups:

- Stationary experiment: the gyroscopic mouse performed with the fastest mean time, the trackball and touchpad ranking the second fastest, the slowest device was the Twiddler2.
- Walking experiment: the trackball and touchpad performed with the fastest mean time, the Twiddler2 was the next fastest, while the slowest device was the gyroscopic mouse.

The trackball and touchpad performed comparably between the two mobility conditions for task completion time and were shown to have superior performance overall for a device to be employed in both the walking and stationary conditions.

Testing the accuracy of the devices indicated that the devices can be placed into the following groups as follows:

- Stationary experiment: the gyroscopic and touchpad mouse reported the lower error rate, while the Twiddler2 and trackball reported the higher error rate. However, a significant difference is reported between the gyroscopic and trackball mouse only for missed dropped locations.
- Walking experiment: the Twiddler2 and touchpad devices performed with the lower error rate, the trackball ranking the next lowest, while the gyroscopic mouse reported the highest error rate. For missed target selections and missed dropped locations no significance was found between the Twiddler2 and touchpad

mouse. In addition, no significance was reported between the Twiddler2 and trackball for missed dropped locations.

The touchpad and Twiddler2 performed comparably between the two mobility conditions for mean total error, however, both the trackball and gyroscopic mouse performed with significantly higher errors while walking as opposed to while stationary.

Survey results obtained from participants rating the "overall operation of device" can be placed into three groups as follows:

- Stationary experiment: the touchpad was reported as the easiest device, the trackball and gyroscopic mouse ranked second, while the Twiddler2 was reported the most difficult to use. The groupings support the participant rankings reported in Table 15.
- Walking experiment: the touchpad and trackball were reported to be the easiest devices, followed by the Twiddler2 ranked second, while the gyroscopic mouse was reported as the hardest device to use. The groupings support the participant rankings reported in Table 15.

The study confirmed that there is a measurable difference in target size and distance combinations presented to the participants. Target sizes of 48 pixels placed at a distance of 300 pixels apart are dragged and dropped significantly faster than any other combination, followed by size and distance combinations of 32x300 and 48x500 performing comparably as the next fastest. The third and fourth times were reported by target and distance combinations of 32x500 and 16x300 respectively. Finally, target sizes of 16 pixels placed at a distance of 500 pixels apart were dragged and dropped the slowest. Not surprisingly, target sizes of 16 pixels placed at either 300 pixels or 500 pixels apart were more error prone than the other size and distance combinations.

Of interest is whether there is an optimal pointing device in terms of operator performance over a suit of tasks and whether certain devices are better suited to certain tasks. The next chapter builds upon this work and evaluates the pointing devices when performing menu selection tasks.

5

Menu Selection User Study

5.1 Introduction

Chapter 4 presented a usability study that compared four commercially available pointing devices performing drag and drop tasks while stationary and while mobile. This chapter further extends the preceding work by evaluating the pointing devices performing an increasingly complex task of menu selection.

Several projects have identified the need for wearable menu interaction and have explored and incorporated the use of menus in the wearable computer interface, however, this has typically involved the use of a dedicated input device in order to interact with the menus presented onscreen. The VuMan [28-32] series of wearable computer and descendants are examples of employing the use of dedicated input devices to interact with on screen objects. Cross et al. [144] implemented a pie-menu interface and used a three button input device (up, down and select) for interaction. Blasko and Feiner [145, 146] use a touchpad device separated into four strips that correspond to a finger of the hand. The onscreen menu is designed to be used specifically with the device and each strip corresponds to a menu. The user glides their finger along the vertical strip to highlight the corresponding menu on screen. KeyMenu [147] is a pop-up hierarchical menu which uses the Twiddler input device to provide a one-to-one mapping between buttons on the keyboard and the menu items presented on the screen. Section 2.3.2 provides further detail regarding previous research into the use of menus for use with wearable computers.

Research into traditional desktop menus has a long rich history, from studies that evaluate menu selection techniques [167, 168, 223], different menu designs [164-166, 169] to the development of models that attempt to predict or improve menu performance [224, 225]. Section 2.4.1.2 provides further detail regarding previous work pertaining to traditional menu research.

In the limited space of wearable usability studies, Witt and Kluge [9] presented a study evaluating three wearable input devices used to perform menu selection tasks. The menu was a list made up of between 4 to 7 items. The input devices consisted of a pointing device (handheld trackball), a novel data glove for gesture recognition and speech recognition. Both laymen and domain experts were evaluated on short and long menu navigation tasks. The trackball mouse outperformed the other devices. For short menu

navigation tasks; laymen performed fastest with the trackball, followed by speech then data glove (statistical difference between the trackball and data glove only). Domain experts performed comparably faster with the trackball and data glove, followed by speech (however, no significant differences were found across the three devices). For long menu navigation tasks, both laymen and domain experts performed faster with the trackball, followed by the data glove, then speech (however no significant difference for laymen was found; no significant difference between trackball and data glove was found for domain experts). Qualitative data from domain experts preferred the hands-free nature of the data glove. Speech interaction was found to be difficult by domain experts who exhibited a wide range of language abilities. Hwang et al. [140] evaluate their novel wrist mounted device (called the FeelTip) against an analogue joystick across four tasks, one of which is 1D menu selection. The menu was a list of 50 items. The FeelTip was reported to perform better than the joystick for the menu and map navigation tasks.

Although menu interaction in a traditional desktop setting has been extensively studied, and while researchers have sought to explore the use of menus in a wearable domain, studies evaluating menu interaction in a wearable context appear to be limited to the aforementioned studies by Witt and Kluge [9] and Hwang et al. [140]. However, in the study presented by Witt and Kluge [9], participants were evaluated while stationary and wore a vest that housed an OQO computer in order to simulate the wearing of a wearable computer. Participants wore a monocular head-worn display. The head-worn display and input devices were actually connected to a stationary computer running the experiment software. In the study presented by Hwang et al. [140] the mobility of the participants and the display device used in order to present the experimental conditions to the participants is unclear. Both studies also limit their evaluation to one style of menu. The study presented in this chapter evaluates participants while wearing a computer on their back and using a head-worn display. The experiments evaluate the participants while stationary and walking and evaluate four different menu structures.

This chapter further extends the previous work presented in the preceding chapters by evaluating the pointing devices performing menu selection. In addition, the study presented in this chapter examines the effectiveness of different menu designs in a wearable context. The devices are evaluated while standing and while walking. In the previously presented drag and drop study, participants were noted to dramatically slow

down their walking speed in order to complete the task. Percentage Preferred Walking Speed (PPWS) is introduced as a further measure in order to provide further insights into mobile wearable interaction. The premise behind measuring PPWS is to assess the impact that interacting with a device has on a user's default walking speed. That is, if the interaction causes the user to slow down, it stands to reason that the device is not as usable while mobile and vice-versa. This method is used by Brewster et al. [204] and Lumsden and Brewster [206] to determine whether the two eyes-free interaction techniques for use with a wearable device have an effect on walking speed. The authors report significant results for PPWS in the study where participants are required to select menu items from a 3D audio radial pie menu using head gestures. Sounds that remained at a fixed position to the user's head requiring the user to simply nod at the appropriate menu selection had less impact on walking speed than the other designs presented. In this condition, participants walked slower at 69% of their normal walking speed as opposed to 47.5% and 48.5% for the other two conditions.

The remainder of the chapter describes the method and results of the study and presents a discussion of the findings.

5.2 Experiment

The usability study presented in this chapter investigates the usability of four commercially available pointing devices while stationary and walking. The task performed by participants was menu selection. Four commercial pointing devices are used (trackball (Section 2.3.3.1), gyroscopic mouse (Section 2.3.3.3), Twiddler2 mouse (Section 2.3.3.4)), and the touchpad (described in Section 2.3.3.2). A tabletop mouse was also included as a benchmark for comparison with traditional desktop user interaction techniques.

The hypotheses of the study were as follows:

- H1: There is a difference between the pointing devices while walking and stationary and therefore, a ranking of the devices can be established.
- H2: A particular pointing device is better suited to a particular movement condition.
- H3: There is a difference between the different menu structures while walking and stationary, and therefore, a ranking of the menu structures can be established.
- H4: A particular menu structure is better suited to a particular movement condition.

- H5: A particular pointing device is better suited to a particular menu structure.
- H6: Users have a preference of pointing device and menu structure.
- H7: Participants walk slower than their preferred walking speed when using a pointing device.
- H8: Pointing devices impact walking speed differently and therefore a ranking can be established.

In doing so, the results will provide valuable insights into the usability of pointing devices and menu structures within a wearable context. In addition, the findings will guide users and designers in selecting a pointing device and menu structure that is well suited and appropriate for the task(s).

5.2.1 Participants

Results were gathered from 20 convenience-sampled computer-literate students and staff at the University of South Australia. There were 17 males and three females; two were left handed and 18 were right handed. The mean age of participants was 29.05 years (SD 6.45). Participants were required to have no prior experience with the pointing devices in a wearable context, to be able to walk and to have normal corrected vision.

5.2.2 Equipment

The experiment was conducted on a Toshiba Laptop Computer (Portégé M200) running the Microsoft Windows XP operating system. The output device used was an optical see-through head-worn display produced by Sony (Glasstron with resolution 800 × 600 SVGA; FoV 30 degrees (h) x 22.5 degrees (v), 38 degrees diagonal). Four commercial pointing devices were used: trackball, gyroscopic mouse, Twiddler2 mouse and touchpad. The computer, wireless receiver and power converter were attached to a small backpack (modified baby carrier seen in chapter 4, Figure 11). The display and computer were operated with battery power.

5.2.3 Software and Data Collection

A custom-built application written in Java coordinated the entire session of tasks. To display a menu, participants were required to select a green start button (size 48×48 pixels) placed in the centre of the screen, seen in Figure 19. Once the start button had

been selected, it was removed, and a menu placed on the screen. Fixed menus were immediately shown on-screen, whereas pop-up menus appeared only after users clicked on the screen.



Figure 19: Green start button to commence menu selection trial

The data recorded included total task and menu selection times in nanoseconds (up to one millisecond resolution) and the number of errors (missed menu items and incorrect menu item selections). Menu selection was timed starting with a click on the green start button and ended when a menu item in a sub-menu was selected. The application continued to present the menu until it was successfully completed (i.e. the correct menu item was selected). In addition to the above data, the supervisor recorded individual lap times, number of laps, distance walked (in meters) and the total task time while the participants completed each task.

5.2.4 Menu Structures

The menu structures evaluated in the study consists of the following: pull down (fixed at top, Figure 20), linear (fixed at bottom, Figure 21), linear pop-up (Figure 22), and pie pop-up (Figure 23). Each menu consisted of two-levels: eight top-level menu items and sub-menus containing eight menu items for each top-level item. Menu selection was modelled on typical menu interaction employed in a standard GUI application. A sub-menu was activated by clicking on its parent item. In addition, the linear pop-up menu allowed a sub-menu to be activated by keeping the cursor over the item's region for a short period of time (333 milliseconds [168]). The target menu item was selected by clicking on the desired item. Selecting a top-level item on the linear fixed menu resulted in the sub-

menu replacing the top-level menu (an additional menu item was added to the end of the menu to allow users to return to the top-level menu if necessary). The pull down and linear fixed menus require travel time to position the cursor over the menu. Although this may be seen to disadvantage those menus, it was decided not to alter the standard operation of the menus. Of interest to this study is the evaluation of the normal operation of the menus. The menu item the participant was required to select was identified by highlighting it green, thus removing the cognitive load associated with reading the menu labels to find the correct target. This practice has been used in other menu studies [167, 168]. Menu sizes are modeled on menus from Microsoft Windows XP. The top-level and sub-level menu items of the pull down menu (Figure 20) occupied 70 and 140 pixels in width respectively, whereas the linear fixed menu (Figure 21) was 70 pixels wide at both levels. The linear pop-up menu (Figure 22) was 140 pixels wide at both levels, and the radius of the pie pop-up menu (Figure 23) was 140 pixels.

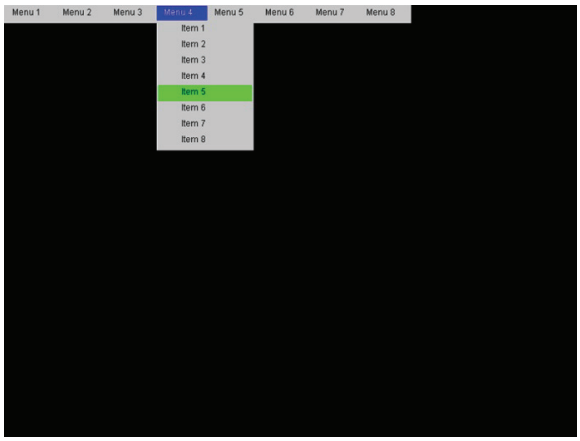


Figure 20: Pull down menu (fixed at top)



Figure 21: Linear fixed menu (fixed at bottom)

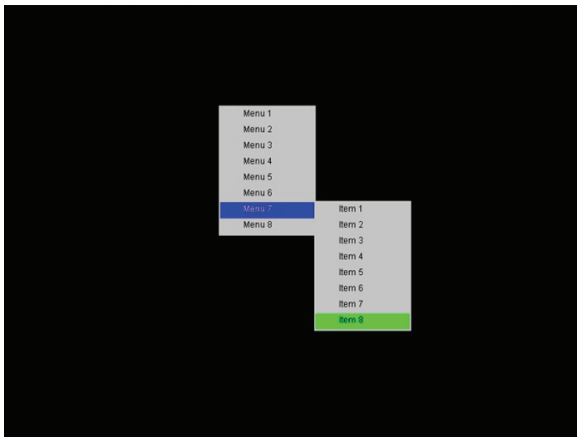


Figure 22: Linear pop-up menu

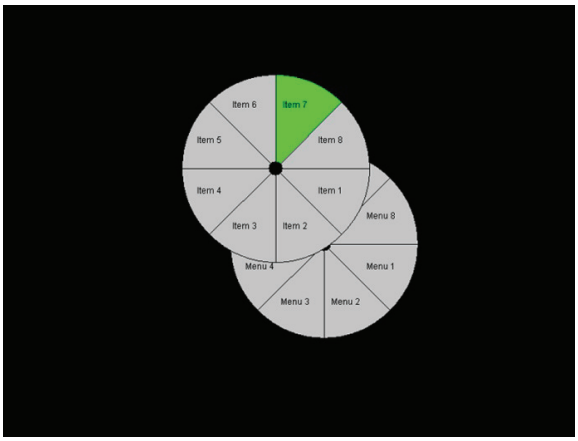


Figure 23: Pie pop-up menu

5.2.5 Design

The independent variables (factors and levels) for the usability study were:

Factor	Levels
Device	Trackball, Gyroscopic mouse, Twiddler2 mouse, Touchpad, Tabletop mouse (benchmark)
Menu	Pull down (fixed at top), linear (fixed at bottom), linear pop-up, pie pop-up
Mobility	Standing, walking

The dependent variables were:

Dependent Measures	Explanation
Total Task time	The total amount of time taken (seconds) from the first green start button selection up to and including the final menu item selection (i.e. the total time taken to perform 20 menu selection operations).
Menu selection time	The time taken (seconds) starting with a click on the green start button and ending when a menu item in a sub-menu was selected (i.e. the time taken to perform one menu selection operation on a given menu structure).
Number of Errors	The total number of errors in a task (20 menu trials) defined as: an incorrect menu selection, a click outside of the menu structure or an accidental collapse of a sub-menu once open.
Walking speed	The walking speed adopted while undertaking a task. Measured by the total distance walked (in meters) divided by the total time taken to repeatedly walk a 15 meter path. Presented in meters per second (m/s). Measured in the walking condition only.

The experiment was a $5\ (device) \times 4\ (menu) \times 2\ (mobility)$ repeated measures design, meaning all participants were tested on all levels (outlined above). To reduce any potential learning effect, each participant performed three blocks of tasks presented in random order. One block consisted of nine tasks, one for each combination of device and mobility (the table-top mouse cannot be used while walking). Each task within a block used a different pointing device and mobility allocated in random order. Twenty menus were presented to the participant made up of four menu structures repeated five times in random order. The menu item to be selected was also presented in random order. A group represented an entire training or experimental session for a participant, with the constraint that there was an equal number of participants who operated each pointing device as the first device of a session.

5.2.6 Procedure

Participants were required to attend two separate sessions, an initial training session (approximately 40 minutes) in order to become familiar with the devices and an experimental session (approximately 90 minutes) which followed the training session. Participants were instructed to use the devices with their dominant hand and to select the menu items as quickly and accurately as possible.

Eighteen stations were positioned along the walls of a quiet, straight hallway, designated by paper posters on the wall. The application prompted the participants to walk to the next indicated station, which provided instructions regarding which pointing device to use and the mobility required for the task. If undertaking the task while stationary, participants would remain at the station. If walking, participants were asked to walk at a normal pace 15 meters along the corridor and back, repeatedly, while completing the task. Participants rested for at least two minutes after completing each block.

5.3 Quantitative Results

This section describes the quantitative results of the experiment. Unless otherwise stated, Analysis of Variance (ANOVA) models were used to determine significance. Mauchly's test was used to determine whether sphericity had been violated. If the assumption of sphericity was violated, degrees of freedom were corrected using Greenhouse-Geisser estimates of sphericity. Statistical significance was set at 0.05. A Bonferroni correction was employed for all post hoc analysis. Trials with errors were left in the dataset for analysis.

5.3.1 Pointing Device Time

Across all devices (excluding the table-top mouse), mobility conditions and participants, the mean total time for one task was 141.23 seconds (SD 42.77). Analysis revealed that there was no effect of group number on mean total time per task $F_{(3.27,310.90)} = 1.95$, $p > 0.05$. A significant effect on mean total time per task was found for the following: block $F_{(1.61,255.75)} = 15.22$, $p < 0.05$; participant $F_{(3.73,85.83)} = 2.86$, $p < 0.05$; mobility $F_{(1.00,19.00)} = 136.59$, $p < 0.05$; and device $F_{(1.69,32.05)} = 56.37$, $p < 0.05$. Furthermore, there was a significant interaction between mobility and device $F_{(1.67,31.74)} = 58.17$, $p < 0.05$, where the standing position allowed consistent, faster completion times than the walking position. Post hoc analysis found that differences between all pairs of devices were

significant, except between the touchpad and Twiddler2 device. The devices can therefore be ordered as follows, the trackball being the fastest, followed by the touchpad and Twiddler2 which were both faster than the gyroscopic mouse.

The mean total time for one task while standing was 109.11 seconds (SD 18.24). While standing, device had a significant effect on mean time per task $F_{(3,57)}$ = 9.40, $p < 0.05$, in particular a significant difference between the trackball and gyroscopic mouse, and trackball and Twiddler2 was found. While walking, the mean total time for one task was 173.35 seconds (SD 76.81). Device significantly effects mean time per task $F_{(1.57,29.81)}$ = 60.79, $p < 0.05$. Pair-wise comparisons indicated significant differences between all devices except for the touchpad and Twiddler2. The table-top mouse was provided as a benchmark and was 39% faster than the trackball in the standing condition and 48% faster in the walking condition.

Timing and error measurements obtained from the study are summarised in Table 16. The table is partitioned by mobility (both mobility conditions, followed by the standing and then walking conditions) and ordered by mean task time.

Table 16: Mean device time (seconds) and error rate (menu selection task)

	Mean time (seconds)		**Mean error rate**	
Device	**Mean**	**Std. dev.**	**Mean**	**Std. dev.**
Mouse	60.68	6.24	2.32	2.32
Both mobility conditions (standing and walking)				
Trackball	108.08	15.23	1.86	0.80
Touchpad	126.03	21.78	3.38	2.09
Twiddler2	137.41	27.88	3.72	3.36
Gyroscopic	193.40	42.93	10.47	7.71
Standing				
Trackball	98.70	16.23	1.58	1.14
Touchpad	109.64	19.04	2.62	1.62
Gyroscopic	111.28	16.99	4.87	4.05
Twiddler2	116.81	16.94	2.02	1.53
Walking				
Trackball	117.45	16.77	2.15	1.06
Touchpad	142.43	29.29	4.15	3.53
Twiddler2	158.01	43.34	5.42	6.10
Gyroscopic	275.52	77.33	16.07	12.94

5.3.2 Pointing Device Number of Errors

Across all devices (excluding the table top mouse), mobility conditions and participants, the mean errors for one task was 4.86 (SD 5.42). No effect of group number on mean error per task was found $F_{(3.30,313.71)}$ = 2.13, $p > 0.05$. Block repetition identified a significant effect $F_{(1.57,249.42)}$ = 5.93, $p < 0.05$, but only between blocks 1 and 3 ($p < 0.05$). Likewise, further analysis evaluating block effect on time per task revealed a significance between blocks 1 and 2 ($p < 0.05$). Although the training session was used to overcome a training effect, a learning effect is evident. Further work in the way of a longitudinal study needs to be done in order to explore the findings. Differences between participants were also identified $F_{(5.44,125.17)}$ = 2.76, $p < 0.05$. Mobility $F_{(1.00,19.00)}$ = 35.17, $p < 0.05$, device $F_{(1.38,26.16)}$ = 17.61, $p < 0.05$ and interactions between both $F_{(1.57,29.81)}$ = 10.08, $p <$ 0.05 all proved significant. In particular, the trackball performed best, followed by the touchpad and Twiddler2 (no significant differences could be identified for this pair); the gyroscopic mouse suffered from the highest error rate.

Variations observed between devices obtained from the standing condition proved significant $F_{(1.67,31.73)}$ = 10.01, $p < 0.05$, in particular when comparing the gyroscopic mouse with the trackball and the Twiddler2. The mean error rate for one task while standing was 2.77 (SD 2.66). A considerably higher error rate of 6.95 (SD 9.05) was reported for the walking condition. Devices also showed significant variation $F_{(1.45,27.60)}$ = 14.89, $p < 0.05$ while walking, with the gyroscopic mouse performing worse than all other devices.

5.3.3 Menu Structure Time

The mean time for menu selections across all conditions (excluding the table-top mouse) was 3.93 seconds (SD 0.60). Overall, the choice of menu structure had a significant influence on mean time for menu selection $F_{(3,57)}$ = 101.13, $p < 0.05$, where the pie pop-up was fastest, followed by the pull-down fixed menu, the linear fixed menu ranked third, and the linear pop-up menu reported the slowest time. All differences were significant (error trials were removed from the analysis). As found in the analysis of mean pointing device time, standing menu selection outperformed walking menu operation $F_{(1.00,79.00)}$ = 502.13, $p < 0.05$. Significant interactions between mobility and menu structure $F_{(3,57)}$ = 32.49, $p < 0.05$ and between pointing device and menu structure $F_{(4.47,84.92)}$ = 8.02, $p <$

0.05 were identified. The latter is illustrated in Figure 24. Furthermore, there is a significant interaction between pointing device, menu structure and mobility $F_{(4.37,83.09)}$ = 5.11, $p < 0.05$, as is shown in Figure 25 for the standing operation and in Figure 26 for the walking condition.

The mean total time for menu selections while standing was 3.38 seconds (SD 0.51) and while walking was 4.49 seconds (SD 0.75). Menu structures resulted in a significant effect on mean time while standing $F_{(2.16,41.06)}$ = 53.85, $p < 0.05$ and while walking $F_{(3,57)}$ = 97.73, $p < 0.05$. In both cases, the pie pop-up was fastest, followed by the pull down fixed, the linear fixed and the linear pop-up menu. All differences with the exception of the linear fixed and the linear pop-up were significant.

Table 17 summarizes the results obtained for the menu structures covered in the experiment (partitioned by menu structure and ordered by mean time for each mobility condition).

Table 17: Mean menu selection time (seconds) and error rate (menu selection task)

	Mean time (secs)		**Mean error rate**	
Menu	**Mean**	**Std. dev.**	**Mean**	**Std. dev.**
Both mobility conditions (standing and walking)				
Pie Pop-up	3.45	.39	.08	.06
Pull down Fixed	3.76	.49	.30	.19
Linear Fixed	4.16	.57	.50	.33
Linear Pop-up	4.35	.52	.14	.07
Sitting (mouse)				
Pull down Fixed	1.86	.16	.14	.20
Pie pop-up	1.88	.19	.03	.06
Linear Fixed	1.95	.17	.25	.28
Linear Pop-up	2.23	.20	.05	.06
Standing				
Pie pop-up	3.08	.40	.03	.03
Pull down Fixed	3.22	.41	.15	.10
Linear Fixed	3.52	.46	.28	.21
Linear Pop-up	3.69	.54	.09	.06
Walking				
Pie pop-up	3.82	.44	.13	.10
Pull down Fixed	4.31	.63	.43	.30
Linear Fixed	4.80	.74	.72	.52
Linear Pop-up	5.01	.56	.18	.11

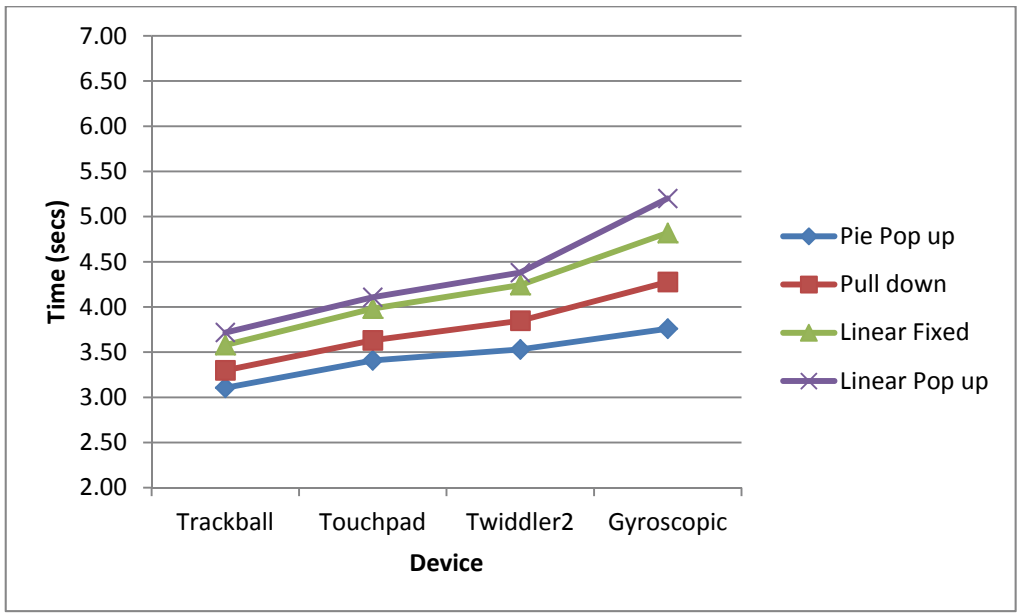


Figure 24: Menu x device interaction both positions (menu selection task)

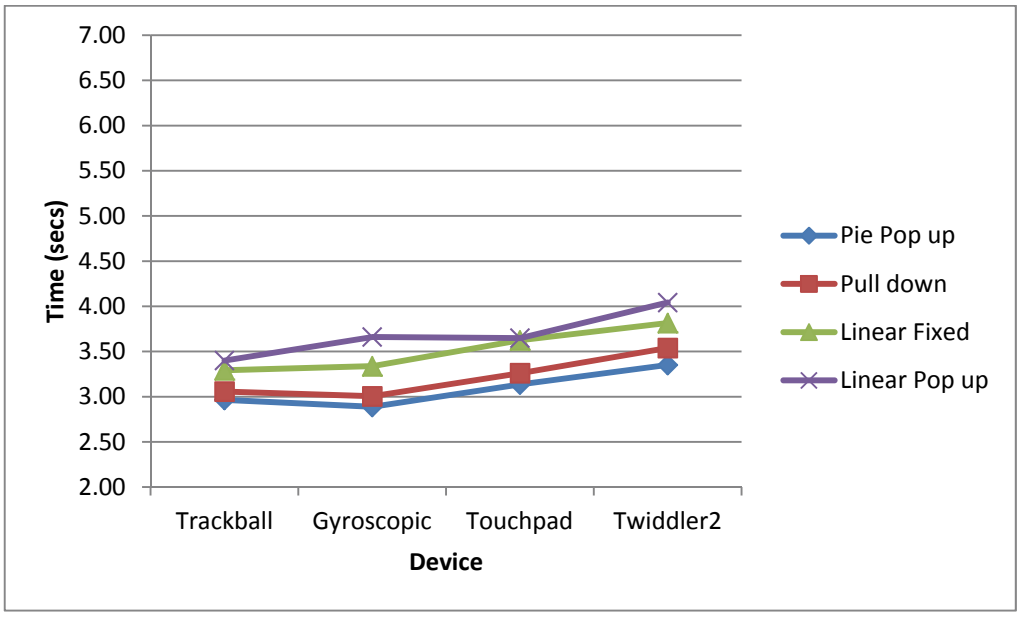


Figure 25: Menu x device interaction standing (menu selection task)

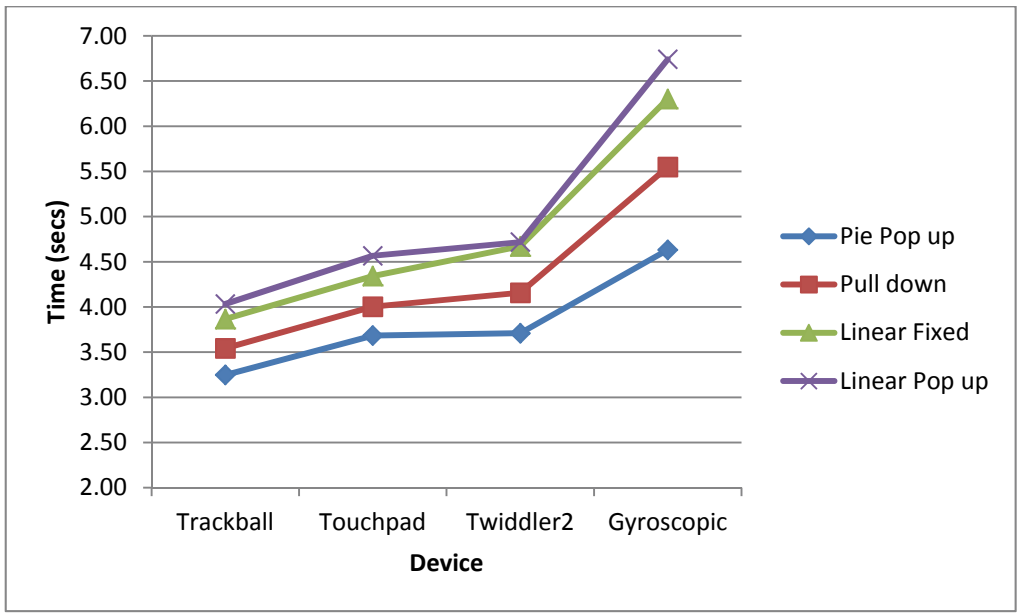


Figure 26: Menu x device interaction walking (menu selection task)

5.3.4 Menu Structure Number of Errors

The mean error rate for menu selections across all conditions (excluding the table-top mouse) was 0.25 (SD 0.25). Menu structure had a significant impact on the mean selection error rate $F_{(1.51,28.63)} = 26.03$, $p < 0.05$. The pie pop-up resulted in the lowest error rate, followed by the linear pop-up menu, the pull down fixed menu, and the linear fixed menu (all differences were significant). Overall, the mean error rates are lower while standing than while walking $F_{(1.00,79.00)} = 48.66$, $p < 0.05$. The mean error for menu selections while standing was 0.14 (SD 0.15), and while walking was 0.37 (SD 0.38). Menu structure was also significant while standing $F_{(1.40,26.65)} = 20.00$, $p < 0.05$ and while walking $F_{(1.57,29.84)} = 21.68$, $p < 0.05$. All pairs were found to be significantly different in the standing condition. However, in the walking condition, differences between the pull down and the linear fixed menu were not significant, nor were those between the linear pop-up and pie pop-up menu structures. Furthermore, significant interactions were found between: mobility and menu structure $F_{(1.65,31.35)} = 11.28$, $p < 0.05$, pointing device and menu structure $F_{(1.52,28.80)} = 13.00$, $p < 0.05$, and mobility, pointing device and menu structure $F_{(1.76,33.45)} = 5.90$, $p < 0.05$.

5.3.5 Top-level Selection Analysis

A top-level selection is a click in order to select one of the eight top-level menu items (i.e. single-level menus). Sub-menu selections are not included in the analysis. This section

describes the results analysed using top-level selections only, that is, the time taken starting with a click on the green start button and ending with a click on a top-level menu item.

5.3.5.1 Pointing Device Top-level Time and Error

Across all devices (excluding the table-top mouse), mobility conditions and participants, the mean total time for one task of top-level menu (single-level menu) selections was 58.00 seconds (SD 25.59). A significant effect on mean total time per task was found for the following: mobility $F_{(1.00,19.00)}$ = 120.16, $p < 0.05$; and device $F_{(1.67,31.68)}$ = 47.70, $p < 0.05$. Furthermore, there was a significant interaction between mobility and device $F_{(1.87,35.52)}$ = 47.40, $p < 0.05$, where the standing position allowed consistent, faster completion times than the walking position. Post hoc analysis found that differences between all pairs of devices were significant, except between the touchpad and Twiddler2 device. The devices can therefore be ordered as follows, the trackball being the fastest, followed by the touchpad and Twiddler2 which performed comparably and were both faster than the gyroscopic mouse.

The mean total time for one task while standing was 45.74 (SD 7.98) seconds. While standing, device had a significant effect on mean time per task $F_{(3,57)}$ = 6.47, $p < 0.05$, in particular a significant difference between the trackball and gyroscopic mouse, and trackball and Twiddler2 was found. While walking, the mean total time for one task was 70.27 (SD 30.81) seconds. Device significantly effected mean time per task $F_{(1.61,30.56)}$ = 51.75, $p < 0.05$. Post hoc comparisons indicated a significant difference between all pairs of devices except for the touchpad and Twiddler2. The table-top mouse was provided as a benchmark and was 36% faster than the trackball in the standing condition and 45% faster in the walking condition.

Timing and error measurements for top-level menu selections obtained from the study are summarised in Table 18. The table is partitioned by mobility (both mobility conditions, followed by the standing and then walking conditions) and ordered by mean task time.

Table 18: Mean top-level (single-level) device time and error rate (menu selection task)

	Mean time (seconds)		Mean error rate	
Device	**Mean**	**Std. dev.**	**Mean**	**Std. dev.**
Mouse	26.56	3.11	0.10	0.16
Both mobility conditions (standing and walking)				
Trackball	45.01	8.07	0.12	0.21
Touchpad	51.60	11.93	0.07	0.15
Twiddler2	56.62	16.27	0.16	0.33
Gyroscopic	78.78	39.21	0.87	1.33
Standing				
Trackball	41.35	7.27	0.08	0.18
Touchpad	46.02	8.26	0.05	0.12
Gyroscopic	46.91	7.64	0.13	0.25
Twiddler2	48.67	7.40	0.08	0.18
Walking				
Trackball	48.67	7.27	0.15	0.23
Touchpad	57.17	12.59	0.08	0.18
Twiddler2	64.58	18.85	0.23	0.42
Gyroscopic	110.65	30.97	1.60	1.57

The mean error rate for top-level menu selections across all conditions (excluding the table-top mouse) was 0.30 (SD 0.77). Mobility $F_{(1.00,19.00)}$ = 29.42, $p < 0.05$, device $F_{(1.20,22.79)}$ = 15.55, $p < 0.05$ and interactions between both $F_{(1.24,23.61)}$ = 12.12, $p < 0.05$ all proved significant. In particular, the gyroscopic mouse suffered from a significantly higher error rate than the other devices.

The mean error rate for one task while standing was 0.09 (SD 0.19). A considerably higher mean error rate of 0.52 (SD 1.03) was reported for the walking condition. Although no significant differences were found between the devices for the standing condition, devices showed significant variation $F_{(1.17,22.28)}$ = 14.40, $p < 0.05$ while walking, with the gyroscopic mouse performing significantly worse than all other devices.

5.3.5.2 Menu Structure Top-level Time and Error

The mean time for top-level menu (single-level menu) selections across all conditions (excluding the table-top mouse) was 2.25 seconds (SD 0.46). Overall, the choice of menu structure had a significant influence on mean time for menu selection $F_{(1.79,33.95)}$ = 29.86, $p < 0.05$. Post hoc comparisons (error trials were removed from the analysis) found that all differences were significant with the exception of the linear fixed and pie pop-up menus. In light of this, the pull-down fixed menu performed with the fastest time,

followed by the linear fixed and pie pop-up menus, and finally the linear pop-up menu reported the slowest time.

Standing top-level menu selection out performed walking menu operation $F_{(1,19)}$ = 212.15, $p < 0.05$. Significant interactions between mobility and menu structure $F_{(3,57)}$ = 14.92, $p < 0.05$ and between pointing device and menu structure $F_{(4.65,88.29)}$ = 7.52, $p <$ 0.05 were identified. The latter is illustrated in Figure 27. Furthermore, there is a significant interaction between pointing device, menu structure and mobility $F_{(4.11,78.06)}$ = 4.03, $p < 0.05$, as is shown in Figure 28 for standing operation and in Figure 29 for the walking condition.

Table 19: Mean menu top-level (single-level) selection time (seconds) and error rate (menu selection task)

	Mean time (secs)		**Mean error rate**	
Menu	**Mean**	**Std. dev.**	**Mean**	**Std. dev.**
Both mobility conditions (standing and walking)				
Pull down Fixed	2.05	0.39	0.01	0.02
Linear Fixed	2.23	0.46	0.02	0.03
Pie pop-up	2.25	0.37	0.02	0.03
Linear Pop-up	2.48	0.50	0.01	0.01
Sitting (mouse)				
Pull down Fixed	0.99	0.08	0.00	0.00
Linear Fixed	1.09	0.10	0.00	0.01
Pie pop-up	1.22	0.14	0.01	0.03
Linear Pop-up	1.37	0.15	0.00	0.01
Standing				
Pull down Fixed	1.81	0.27	0.00	0.00
Linear Fixed	1.91	0.25	0.00	0.01
Pie pop-up	2.01	0.29	0.01	0.01
Linear Pop-up	2.10	0.33	0.01	0.01
Walking				
Pull down Fixed	2.29	0.34	0.02	0.03
Pie pop-up	2.48	0.28	0.04	0.03
Linear Fixed	2.54	0.39	0.03	0.04
Linear Pop-up	2.87	0.31	0.01	0.02

The mean total time for top-level menu selections while standing was 1.96 seconds (SD 0.30) and while walking was 2.55 seconds (SD 0.39). Menu structures resulted in a significant effect on mean time while standing $F_{(1.97,37.49)}$ = 14.92, $p < 0.05$ and while walking $F_{(1.96,37.32)}$ = 33.04, $p < 0.05$. In both conditions, all differences with the

exception of the linear fixed and the pie pop-up were significant. In addition, the pie pop-up and linear pop-up were not significant in the standing condition only. In both conditions, the pull down fixed menu outperformed the other menu structures, the linear fixed and the pie pop-up performed comparably and the linear pop-up was the slowest of the menu structures. Table 19 summarizes the results obtained from top-level menu selections for the menu structures covered in the experiment (partitioned by menu structure and ordered by mean time for each mobility condition).

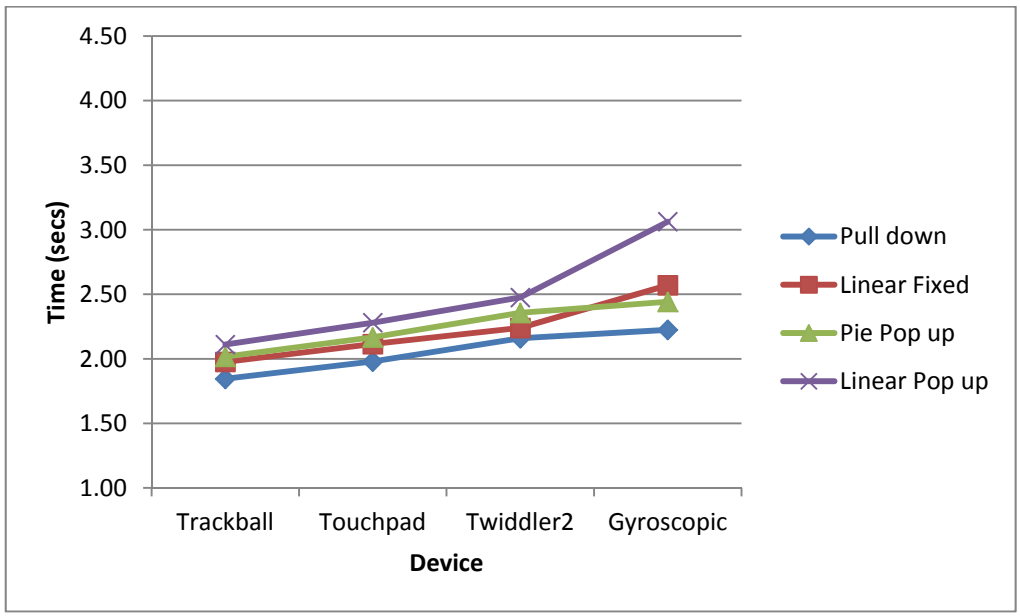


Figure 27: Menu x device interaction (top-level selections) both positions (menu selection task)

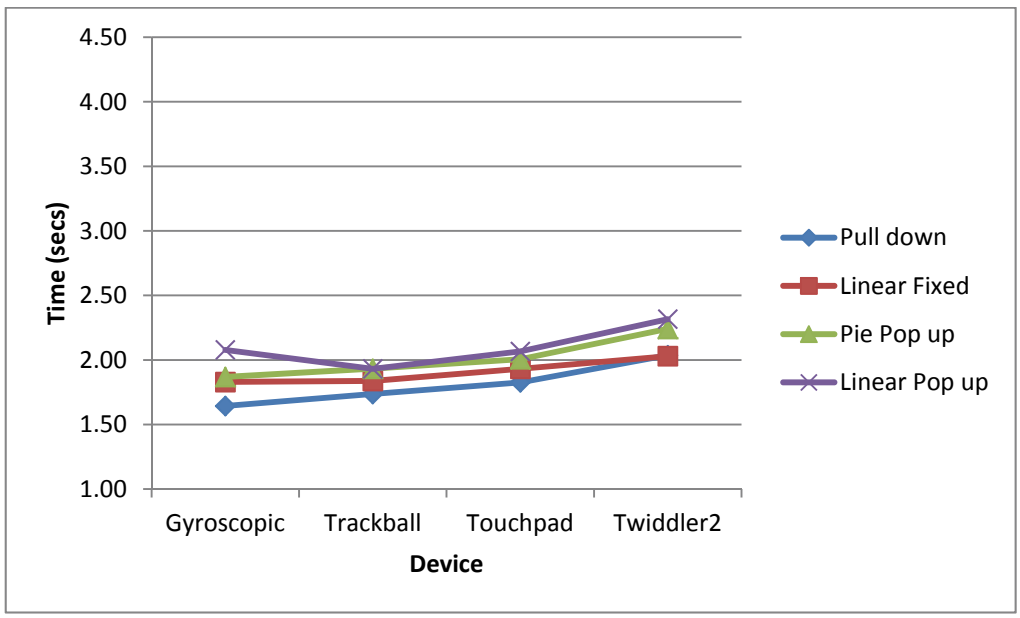


Figure 28: Menu x device interaction (top-level selections) standing (menu selection task)

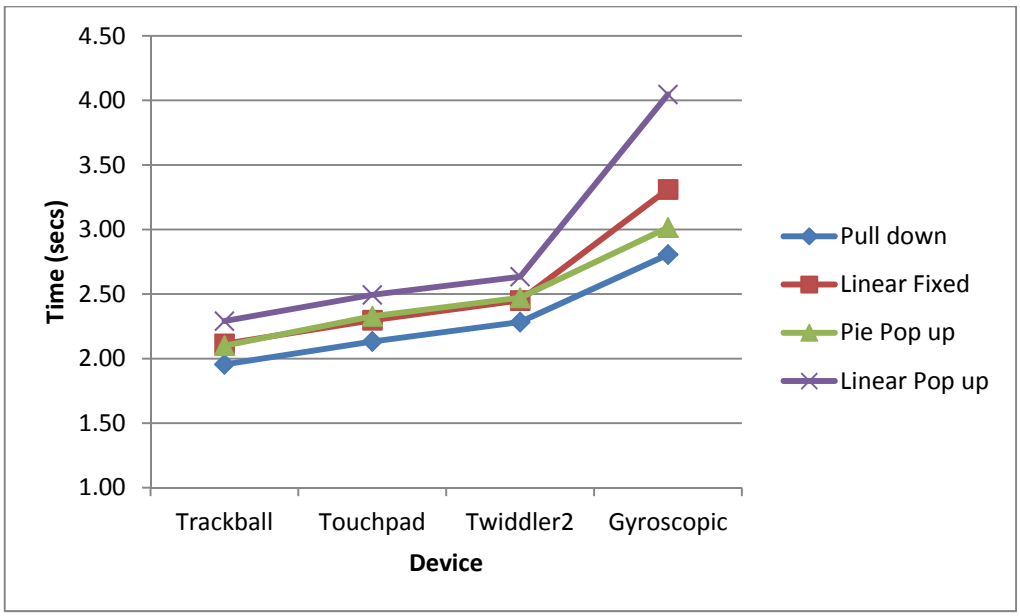


Figure 29: Menu x device interaction (top-level selections) walking (menu selection task)

The mean error rate for top-level menu selections across all conditions (excluding the table-top mouse) was 0.2 (SD 0.02). Menu structure had a significant impact on the mean selection error rate $F_{(3,57)} = 4.51$, $p < 0.05$. The pull down fixed and linear pop-up menus performed comparably, likewise the linear fixed and pie pop-up menus performed with comparably greater errors (significant difference was found between the pull down fixed and pie pop-up menu pair only). Overall, the mean top-level error rates are lower while standing than while walking $F_{(1,19)} = 29.09$, $p < 0.05$. Furthermore, significant interactions were found between mobility and menu structure $F_{(3,57)} = 4.96$, $p < 0.05$ and mobility, pointing device and menu structure $F_{(3.56,67.59)} = 2.69$, $p < 0.05$. No significant interaction was found between pointing device and menu structure.

The mean error for top-level menu selections while standing was 0.004 (SD 0.01), and while walking was 0.03 (SD 0.03). Menu structure was significant while standing $F_{(1.76,33.49)} = 3.74$, $p < 0.05$ however post hoc analysis revealed no significant differences between pairs. Menu structure was significant while walking $F_{(3,57)} = 4.86$, $p < 0.05$. A significant difference was found between the pie pop-up and linear pop-up.

5.3.6 Walking Speed

This section describes the results of the experiment conducted to determine the effect of the wearable pointing devices on walking speed. In order to calculate participants' natural preferred walking speed (PWS) when not interacting with the pointing devices,

participants were asked to walk 5 laps of a predetermined 15 meter path along a corridor. The walking speeds of the five laps were averaged to ascertain the participants' preferred walking speed. This practice is found in [124, 204-206]. Preferred Walking Speed (PWS) is presented in meters per second (m/s) and is computed by dividing the distance walked by the time taken to walk said distance. That is, total distance (meters) walked divided by the total time taken (seconds). Table 20 presents the mean walking speeds over all participants wile interacting with each of the devices. Preferred walking speed (PWS) is the baseline condition measuring the mean walking speed of participants without the use of a pointing device.

Across all devices and participants, the mean walking speed (excluding the preferred waking speed condition) while interacting with a pointing device for one task was 0.77 m/s (SD 0.23). Participants' natural preferred walking speed (PWS), that is, without the use of any device, was 1.98 m/s (SD 0.57). This presents an average drop in participants PWS by 61% when interacting with a pointing device.

Table 20: The mean preferred walking speed (baseline), and mean walking speeds while interacting with each of the pointing devices. (menu selection task)

Walking Speed (m/s)	Mean	Std. dev.
Baseline (PWS)	1.98	0.57
Trackball	0.87	0.20
Touchpad	0.81	0.21
Twiddler2	0.81	0.21
Gyroscopic	0.58	0.18

Analysis of walking speed across the five levels (that is, the four devices and the baseline PWS) revealed a main effect $F_{(1.17,22.19)} = 100.76$, $p < 0.05$. Post hoc analysis revealed that there was a significant affect for all pairs except between the touchpad and Twiddler2. In light of this, it can be concluded that participants walked significantly faster when walking at their preferred walking speed in contrast to walking while using the pointing devices and the devices can therefore be placed in three groups dependent upon their impact on walking speed. Participants walked closer to their preferred walking speed while using the trackball mouse (i.e. the use of the trackball had the least impact on the participants' walking speed), the touchpad and Twiddler2 performed comparably ranked second, while

participants walked the slowest when using the gyroscopic mouse (i.e. the use of the gyroscopic mouse had the most impact on the participants' walking speed).

Across all devices and participants, the mean Percentage Preferred Walking Speed (PPWS) for one task was 41.59% (SD 16.20). The mean PPWS per task was significantly affected by pointing device $F_{(3,57)} = 49.21$, $p < 0.05$. A post hoc analysis was performed on all pairs of devices and it was found that there was a significant effect for all pairs except between the touchpad and trackball and touchpad and Twiddler2. The average PPWS for the gyroscopic mouse was 31.56% (SD 14.51), the Twiddler2 43.87% (SD 15.59) and the touchpad 43.66% (15.37) performed comparably, followed by the trackball 47.28% (SD 15.87). The trackball allowed participants to walk the fastest at 47.28% of their preferred walking speed while performing menu selection tasks. The gyroscopic mouse resulted in participants walking the slowest at 31.56% of their PWS. The percentage preferred walking speed for all participants with each device is depicted in Figure 30.

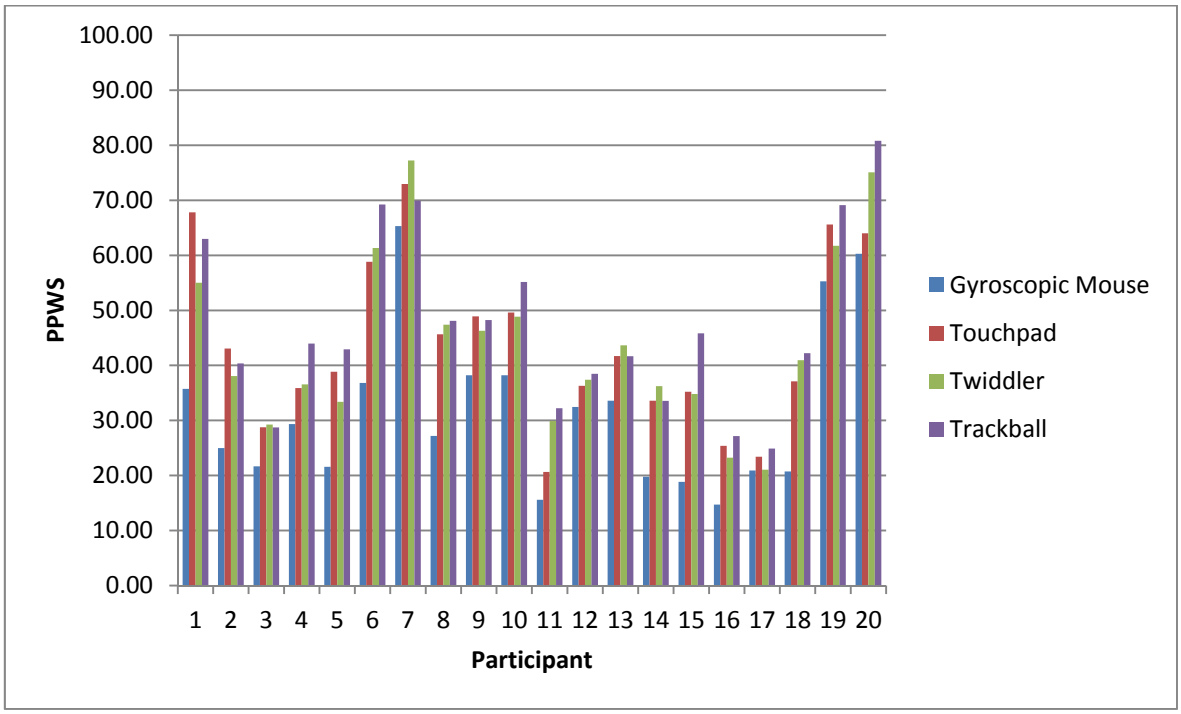


Figure 30: Percentage preferred walking speed (PPWS) for all participants and devices. The preferred walking speed is represented by the 100% line. (menu selection task)

Table 21: Mean rating for general and fatigue attributes for both mobility conditions. Standard deviation in parenthesis. (menu selection task)

	Standing		
Device	**General**	**Fatigue**	**Mean total rating**
Trackball	5.65 (0.28)	6.04 (0.50)	5.77 (0.40)
Touchpad	5.81 (0.18)	5.55 (0.61)	5.73 (0.37)
Twiddler2	4.30 (0.26)	5.28 (1.21)	4.61 (0.81)
Gyroscopic mouse	3.77 (0.63)	4.92 (1.12)	4.13 (0.95)
	Walking		
Device	**General**	**Fatigue**	**Mean total rating**
Trackball	5.33 (0.33)	5.93 (0.68)	5.52 (0.53)
Touchpad	5.25 (0.32)	5.38 (0.66)	5.29 (0.43)
Twiddler2	4.19 (0.22)	5.17 (1.19)	4.49 (0.80)
Gyroscopic mouse	2.55 (1.03)	4.54 (1.21)	3.18 (1.41)

5.4 Participant Survey

Participants were required to complete an exit questionnaire where they were asked to rate the devices on a 7 point scale in terms of overall reaction and experience using the device. The first eleven questions were concerned with general attributes such as smoothness, speed, and accuracy (scale of 1 very difficult to 7 very easy), while the remaining five questions were concerned with neck, shoulder, arm, wrist and finger fatigue (scale of 1 very high to 7 none). The mean rating across all participants and attributes for each of the devices and mobility conditions is as follows: trackball 5.64 (SD 0.48), touchpad 5.51 (SD 0.46), Twiddler2 4.55 (SD 0.79), and gyroscopic mouse 3.65 (SD 1.28).

The mean total rating across all participants and attributes (general and fatigue) for the standing condition is as follows: trackball 5.77 (SD 0.40), touchpad 5.73 (SD 0.37), Twiddler2 4.61 (SD 0.81), gyroscopic mouse 4.13 (SD 0.95). The mean total rating across all participants and attributes (general and fatigue) for the walking condition is as follows: trackball 5.52 (SD 0.53), touchpad 5.29 (SD 0.43), Twiddler2 4.49 (SD 0.80) and gyroscopic mouse 3.18 (SD 1.41). Table 21 lists the mean rating for the general and fatigue questions for both mobility conditions.

Participants were asked which device and menu they preferred to use in a wearable context: eleven preferred the trackball, eight the touchpad, while one preferred the Twiddler2 (supporting hypothesis 6). Eighteen preferred the pie pop-up menu, while two preferred the pull down menu (supporting hypothesis 6). Participants were asked which

menu structure they preferred to use with a specific device. Figure 31 illustrates that the pie pop-up menu is the favourable choice for all pointing devices, followed by the pull down menu.

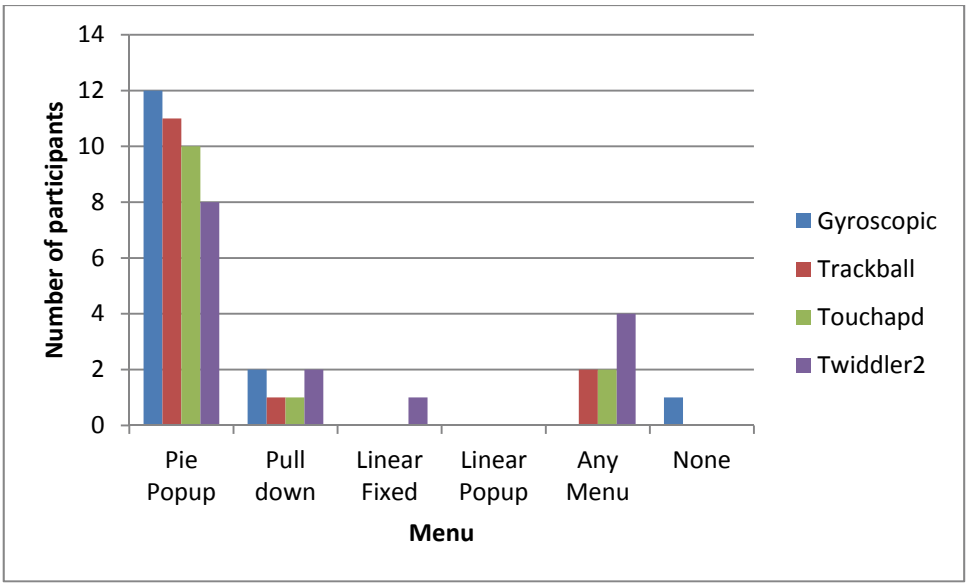


Figure 31: Menu structure preferred for use with specific pointing device. (menu selection task)

When asked, eleven participants indicated they would prefer to use a device attached to the body, however, eight were not receptive to the idea. Participants were evenly split (ten apiece) when asked about their preference for using a hand held device. The preferred positions for attaching a device to the body was identified as: six preferring the forearm, four the wrist, three the arm, two the fingers, two the hand and one for the side of thigh. Fourteen participants indicated that the device they would consider using attached to their body was the touchpad, four indicated the trackball and two stated the Twiddler2.

Figure 32 along with Figure 33 depict the mean ratings across all participants for each general attribute for each device and for both mobility conditions. Both graphs illustrate a preference for the trackball and touchpad devices (supporting hypothesis 6). Participants report the gyroscopic mouse caused wrist and arm fatigue, while the Twiddler2 caused a tiring of the fingers.

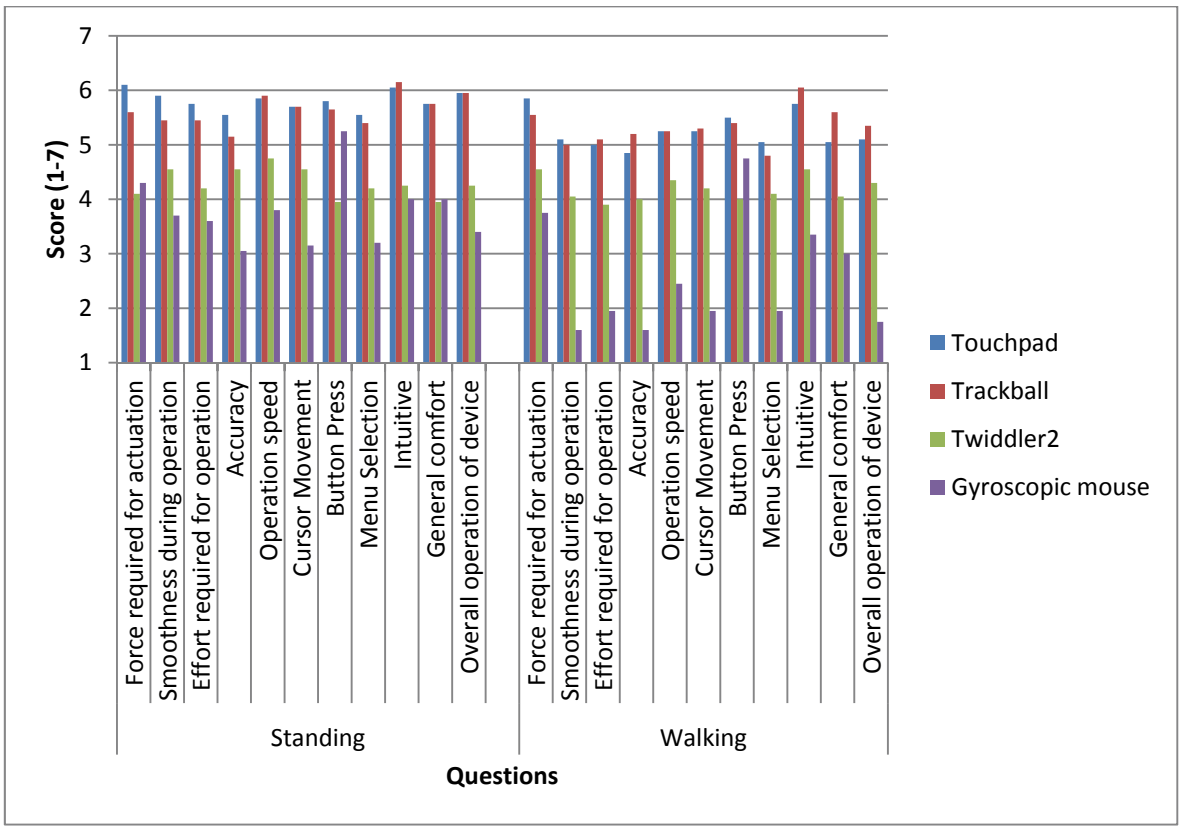


Figure 32: Mean values of general attributes. (menu selection task)

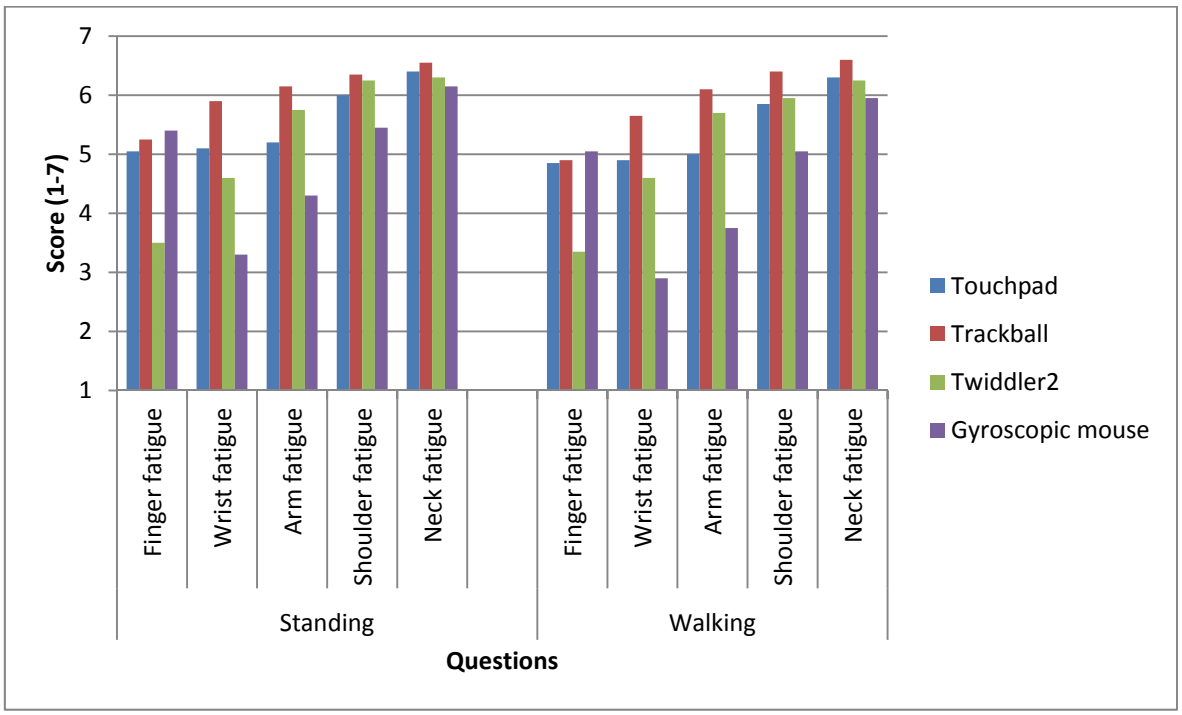


Figure 33: Mean values of fatigue attributes (menu selection task)

5.5 Discussion

This section presents the discussion pertaining to the results of the study.

5.5.1 Pointing Devices

This study confirms that there is a significant difference in task time and number of errors when performing menu selection tasks with pointing devices (supporting hypothesis 1). In both the standing and walking movement conditions, the trackball performed with the fastest mean time and lowest error rate per task (supporting hypothesis 2). The touchpad and Twiddler2 performed comparably with the second fastest mean time and error rate per task. The gyroscopic mouse ranked last with the slowest time and highest error rate. Analysis of the standing condition reports no significant difference between the touchpad, gyroscopic mouse and Twiddler2.

In the previous selection study [226] presented in Chapter 3, the gyroscopic mouse was the fastest and least accurate device. In the previous drag and drop study [134] presented in Chapter 4, the gyroscopic mouse was the fastest and most accurate device while stationary. The results obtained from this study suggest that the gyroscopic mouse is a less favourable choice when precise menu selection is required, such as the steering required for the linear pop-up menu. The gyroscopic mouse seems to favour coarse mouse movements, therefore, it may be a suitable choice if used with a pie menu.

Consistent with the findings in the walking drag and drop study, the gyroscopic mouse was the slowest and least accurate device. Observations from the drag and drop study were that while task time and error rate are valuable and necessary measures, they provide little information pertaining to the quality of walking. For example, participants were noticed to slow down considerably while walking with the gyroscopic mouse (the inertial sensing technology is sensitive to vibration making it almost impossible to use while walking). The trackball was the second fastest device in the previous selection study [226]. In the drag and drop study [134], the trackball and touchpad were comparably the fastest devices while walking and the second fastest devices while stationary. These findings along with similar findings in this study seemingly make the trackball or touchpad a favourable choice for use in a wearable context over all the interaction models (selection, drag and drop and menu selection) and over both mobility conditions

(standing and walking). A noted disadvantage of the touchpad over the trackball is the need to use two hands for input. Although it is possible to place the touchpad in a number of different positions on a person's body [151], it is recommended that it be placed in a position that minimizes the effect of the movement of the body while walking. Qualitative feedback indicated that participants' preferred to occupy only one hand (as opposed to two) while interacting with the wearable computer and also considered the trackball and Twiddler2 more natural as their hand was able to be held in any position. Participants liked the idea of an isometric joystick for cursor control; however, the biggest challenge facing the Twiddler2 is its form factor. The Twiddler2 reported a higher level of finger fatigue than the other devices. A more ergonomic design, perhaps in the way of the trackball device, would see a more favourable response by participants and better performance.

Wrist and arm fatigue was also reported to be a problem with the gyroscopic mouse as seen in Figure 33. The gyroscopic mouse was rated to cause considerably higher fatigue than the other devices. Notably, wrist and arm fatigue is also a problem with the touchpad device as participants are required to hold their arms in front of them while operating the device. Given that both arms are in front of the participant, the natural movement of the arms while walking may affect the selection of sub-menu targets, i.e. movements that require precision. The Twiddler2 and trackball devices however are able to be operated with the arm naturally placed by the participants side (not forced into any position), as a result, scoring low in arm and shoulder fatigue. Finger and wrist fatigue is a problem when using the Twiddler2, however, qualitative feedback reports that participants found cursor movement to be relatively stable while walking. Written feedback requested an improved form factor for the Twiddler2 device. Participants reported that selection of a target required applying force to the back of the device, however if the participants finger was still on the trackpoint situated at the back of the Twiddler2, this would cause the cursor to move making the selection of targets difficult. Participants needed to remove their thumb before selecting or learn to apply pressure with a different part of the hand. It may take some time for participants to become comfortable and familiar with the isometric nature of the trackpoint, with some reporting that the trackpoint was difficult to "get right". The trackball appears to be the preferred choice for use in a wearable context while walking, although for activities that do not involve sustained use (as fatigue may be a problem), the touchpad would also be suitable.

Perhaps the reason that the trackball is the preferred choice is because the ball allows for fast coarse movements to menu targets, and also allows as one participant noted, the somewhat seamless change from coarse, fast movements to slow accurate movements.

5.5.1.1 Pointing Device Top-level Selections

Over both movement conditions, the trackball performed with the fastest mean time for top-level selections, this was followed by the touchpad and Twiddler2 (performing comparably) with the second fastest mean time and lastly the gyroscopic mouse performed with the slowest mean time. The gyroscopic mouse also performed with the highest error rate (although not significantly different in the standing condition).

5.5.2 Menus

This study demonstrated a significant difference in speed and accuracy when performing menu selection tasks with different menu structures (supporting hypothesis 3). Similarly to Callahan et al. [166], it was found that pie menus performed better than linear menus in terms of menu selection time and error rate in both movement conditions (supporting hypothesis 4). All pointing devices reported the fastest time with the pie menu. The pull down fixed menu reported the second fastest time, followed by the linear fixed menu. The linear pop-up resulted in the slowest mean selection time and second lowest error rate, this is perhaps due to the precise steering required to select sub-menu items. The findings in this study also confirm Walker and Smelcer's [165] result, that pull down menus are faster than walking menus (the latter are equivalent to the linear pop-up used in this study). Walker and Smelcer [165] also observed that impenetrable borders were effective in decreasing selection time. This observation is perhaps an insight into why the pull down menu reported the second fastest time. The top and bottom of the screen in this case acted as an impenetrable border, whereby participants were able to make long movements towards the menu item without overshooting the target. Another reason perhaps is that participants were familiar with this style of menu. Of note is that the fixed linear menu suffered from the highest error rate. A possible explanation is that participants often failed to see the menu at the bottom of the screen, and then clicked on the screen thinking they were required to pop-up a menu. Larger linear menu items would make selection easier. In both the standing and walking conditions, the linear fixed

and linear pop-up menus reported the slowest selection times with no significant difference between them; interestingly, both menu structures rely on moving the cursor horizontally to select sub-menu items.

5.5.2.1 Menu Top-level Selections

Interestingly, for top-level menu selections, the pull down menu performed significantly faster over both mobility conditions, this was followed by the linear fixed and pie pop-up menus (performing comparably). A possible reason being that perhaps the pie pop-up menu suffered from the delay of having to click on the screen in order to pop-up the menu. Again the pull down menu takes advantage of impenetrable borders that allowed participants to make large coarse movements toward the menu items without overshooting the target. The linear pop-up menu performed significantly slower than the other menus. Although selecting top-level menu items only, perhaps the heights of the menu items still require a level of precise, fine grain movements which hamper selection times.

5.5.3 Combined Results of Menus and Devices

In light of the above, the trackball is seemingly the best choice of device for use with any of the menu structures and for use while walking or standing in a wearable context. Similarly, the pie pop-up menu is the best choice of menu for use with any of the pointing devices and for use while walking or standing in a wearable context. The combination of the trackball and the pie pop-up menu allows the fastest selection time and lowest error rate for both movement conditions (supporting hypothesis 5). The touchpad, Twiddler2 and gyroscopic mouse are comparably the next fastest devices when used with the pie pop-up menu over both conditions. As highlighted in Figure 25, the gyroscopic mouse led to a slightly faster selection time than the trackball for both the pie pop-up and pull down menus when standing. However, this difference is not statistically significant.

In the case where a pie menu is not appropriate as the interaction technique, the use of a pull down menu could form a suitable choice, performing with the next best time for use with any of the pointing devices while walking or standing. Teamed with the touchpad, the pull down menu reported the second fastest time. The gyroscopic mouse and Twiddler2 performed comparably, and reported the slowest times over both conditions

(seen in Figure 24). The slowest menus over all the devices in a wearable context are the linear fixed and linear pop-up menus. The precise steering necessary to select a sub-menu in the linear pop-up menu makes it a poor choice while walking.

Interestingly, some of the times reported by the trackball and touchpad in the standing condition, overlap with the times reported by the mouse. Further work, perhaps a longitudinal study, is needed to ascertain whether familiarity with the devices will produce speeds closer to table-top mouse speeds.

5.5.3.1 Combined Menu and Device Top-level Selections

When considering single-level menus only, the trackball remains as seemingly the best choice of device for use with any of the menu structures and for use while walking or standing in a wearable context. In contrast to two-level menus, the pull down menu is the best choice of menu for use with any of the pointing devices and for use while walking or standing in a wearable context. Over both movement conditions (seen in Figure 27), the trackball teamed with the pull down menu enables the fastest selection time along with a low error rate. In the standing condition only (seen in Figure 28), the gyroscopic mouse when teamed with the pull down menu performed with the fastest selection time, again validating the premise that the gyroscopic mouse tends to perform better when coarse mouse movements are required as found in the previous selection study [226] and in the standing condition of the drag and drop study [134]. The linear pop-up menu performed with the slowest selection time in the walking condition (seen in Figure 29) for use with any of the pointing devices.

5.5.4 Walking Speed

In contrast to Mizobuchi et al. [209] and Schildbach and Rukzio [118] who found that the amount that participants slowed down was not affected by key (no significance) or target size (no significance), this study revealed that the device in use did impact on the speed at which participants walked (depicted in Table 20). Mizobuchi et al. [209] found that although the participants slowed down considerably while entering text, the amount they slowed was a uniform amount necessary to make text entry achievable, the amount they slowed was not affected by key size. However, the results of this study revealed that the rate at which participants slowed down depended on which pointing device they were

using (supporting hypothesis 8). Typically, participants seemed to walk more confidently and faster while using the trackball. However, when using the gyroscopic mouse, participants slowed down to almost a stop in order to select menu targets (also contributing to the large amount of variation). The gyroscopic mouse is susceptible to vibration noise when walking making menu selection extremely difficult. Given the inertial sensing technology (for example, accelerometer) used in the gyroscopic mouse, it is a poor choice to be used while walking. Interestingly, there is a large amount of variation in the gyroscopic mouse, some participants were able to use the trigger to stabilise the cursor to make menu selection easier and faster while walking.

Like Pirhonen et al. [205], PPWS was found to be a useful measure in measuring usability while mobile. The trackball enabled participants to walk closest to their natural preferred walking speed than the other devices (47.28% of PWS). The touchpad and Twiddler2 were comparably ranked second, and not surprisingly, the gyroscopic mouse ranked poorly compared with the other devices.

As previously mentioned, the participants in the study walked with a normal, preferred walking speed of 1.98 m/s. This seems to be slightly higher than normal walking speeds [227, 228] and also higher when compared to the natural walking speeds described in other studies, for example: Yatani and Truong [210] report a natural walking speed of 1.06 m/s, Schildbach and Rukzio [118] report 1.18 m/s, Bergstrom-Lehtovirta et al. [120] report 1.08 m/s and Vadas et al. [212] report 1.20 m/s. However, when walking and interacting with the pointing devices, participants walked with a mean speed of 0.77 m/s. This is a 61% decrease from PWS for menu selection. The reduction in PWS is quite large in contrast to other studies where a decrease from PWS was as follows: while performing text entry 50% [210]; while reading 27% [118] and 14% [212]; and while performing selection tasks 25% [118] and 24% [120]; and while performing visual search took 22.21% [211] longer than the normal walking speed. Although the decrease from PWS was found to be larger than other studies, the walking speed participants slowed too appears to be comparable, for example: in text entry tasks participants walked at 0.49 m/s [209] and 0.53 m/s [210]; in reading tasks participants slowed down to 0.79 m/s [118] and 1.03 m/s (audio condition) and 0.91 m/s (visual condition) [212]; in selection tasks, participants slowed to 0.83 m/s [120] and 0.90 m/s [118]. The slightly higher preferred walking speed

than reported in the other studies mentioned previously is perhaps the reason for the larger decrease from PWS for the menu selection tasks.

Participants walked on average 41.59% of their preferred walking speed while performing menu selection tasks. When evaluating eyes-free interaction techniques using sounds and head nodding gestures, Brewster et al. [204] and Lumsden and Brewster [206] found that egocentric sounds had less impact on walking speed causing participants to walk at 69% of PWS than the other designs presented which were 47.5% and 48.5% of PWS. The latter reductions in PWS when compared to this study are similar.

While undertaking the menu selection tasks, participants walked with speeds ranging from 14.70% to 80.82% of their preferred walking speed. Large variance of preferred walking speed is not uncommon [204, 206]. The percentage preferred walking speed (PPWS) for all participants with each device is depicted in Figure 30. Notably, all participants walked slower than their preferred walking speed (supporting hypothesis 7). Interestingly, only three participants walked at more than 60% of their preferred walking speed with three devices, the Twiddler2, touchpad and trackball. Only one participant walked at 80% of their walking speed and that was with the trackball. Three participants walked at less than 20% of their preferred walking speed with the gyroscopic mouse. Fourteen participants walked less than 50% of their preferred walking speed across all four devices. It is evident from the findings that interacting with a device while mobile is costly. As found by Oulasvirta [121], the cognitively costly nature of mobile interaction affects not only the secondary task being undertaken (i.e. walking), but also slows, stops or postpones interaction with a mobile device. Although a learning effect is not evidenced over the blocks ($F_{(2,158)} = 0.25$, $p > 0.05$), it would be interesting to determine whether repeated exposer to the devices while walking would enable participants to walk closer to their normal walking speed.

5.6 Conclusion

This chapter presented a usability study comparing four menu structures and four pointing devices for use with wearable computers while stationary and walking. The trackball and pie pop-up menu individually resulted in the fastest mean time and lowest error rate over both the walking and standing conditions (for two-level menus).

The study confirms that there is a measurable difference between pointing devices when performing two-level menu selection tasks in a wearable context.

- Standing condition: the trackball performed with the fastest mean task completion time, followed by the touchpad, gyroscopic mouse, and the Twiddler2 performing with the slowest mean time. A significant difference was found between the trackball and gyroscopic mouse, and trackball and Twiddler2. The trackball performed with least amount of errors, followed by the Twiddler2 and Touchpad performing comparably second, the gyroscopic mouse suffered from the highest error rate. A significant difference was found when comparing the gyroscopic mouse with the trackball and the Twiddler2 mouse.
- Walking condition: the trackball being the fastest, followed by the touchpad and Twiddler2 (no significant difference between this pair) which were both faster than the gyroscopic mouse. The trackball performed with the least amount of errors, followed by the touchpad and the Twiddler2. The gyroscopic mouse performed significantly worse with the most amount of errors than all the other devices.

The study confirms that there is a measurable difference between menus when performing two-level menu selection tasks in a wearable context.

- Stationary condition: menus were selected the fastest with the pie pop-up, followed by the pull down fixed ranked second, the linear fixed and the linear pop-up menu ranked third performing comparably (no significant difference could be identified for this pair). The pie pop-up menu performed with the fewest errors, followed by the linear pop-up, pull down fixed and lastly the linear fixed. All differences were significant.
- Walking condition: menus were selected the fastest with the pie pop-up, followed by the pull down fixed ranked second, the linear fixed and the linear pop-up menu ranked third performing comparably (no significant difference could be identified for this pair). The pie pop-up and linear pop-up menus (performed comparably) and with significantly fewer errors than the pull down fixed and linear fixed menus (also performing comparably).

There is a measurable difference in walking speed when performing menu selection tasks with different pointing devices when walking. The introduction of PPWS is useful as a

measure to provide insight into the usability of an interaction technique while mobile. As identified in the drag and drop study [134], found by Oulasvirta [121] and confirmed in this study, mobile interaction impedes both the act of walking and interacting with a mobile device. Participants were noted to slow down their walking when using the pointing devices to interact with a wearable and also increase the time taken to perform menu selection tasks. The trackball had the least impact on walking speed allowing participants to walk closest to their preferred walking speed (47.28% of their PWS) while performing menu selection tasks. The Twiddler2 43.87% and the touchpad 43.66% ranked comparably second while the gyroscopic mouse ranked last causing participants to walk the slowest (31.56% of their PWS).

In both movement conditions (two-level menus), the trackball performed with the fastest mean time and lowest error rate per task. The table-top mouse was provided as a benchmark and was 39% faster than the trackball in the standing condition and 48% faster in the walking condition for two-level menu selection tasks. Pie menus (two-levels) performed with the fastest menu selection time and error rate. For two-level menus, the combination of the trackball and pie pop-up menu is a favourable choice for use in a wearable context. For single-level menus, the combination of the trackball and the pull down menu is the favourable choice over both mobility conditions. The subjective results reported by participants support the quantitative findings.

The next chapter describes the final in a series of studies designed to evaluate the four pointing devices over a suite of interaction tasks. The following chapter evaluates the learnability of the pointing devices by means of an extended study (repeated exposure to the devices over time).

6

Learnability User Study

6.1 Introduction

Chapter three, four and five present the usability studies that compared the four pointing devices performing selection, drag and drop and menu selection tasks respectively. The usability of the pointing devices were evaluated by adopting the usability measures of efficiency, effectiveness and satisfaction as defined in the ISO 9241-9 [11] standard. The previous studies presented in this dissertation predominantly use the measures of task completion time (efficiency), error rate (effectiveness) and questionnaires (satisfaction) in order to evaluate the usability of the devices. In addition to the attributes of efficiency, errors and satisfaction, Nielsen [12] includes learnability and memorability. Learnability has been identified as an important factor in usability and as described by Nielsen [12], refers to the system as being easy to learn. Ease of learning relates to a novice user's experience with a system. Novice users will typically experience a steep learning curve that flattens out with exposure to the system. This chapter extends the previous usability studies presented in this dissertation by evaluating the pointing devices over time. This study seeks to understand the effects of repeated exposure to the pointing devices via an extended study. Of interest is the learnability of the four pointing devices. As described in part 11 of the ISO 9241 standard [162], learnability can be measured by either the comparison of the usability of a product of a user over time, or the comparison of usability of a product for an experienced and inexperienced user. This study will measure the learnability of the pointing devices by comparing the usability of the devices for participants over time. The usability measures described in the ISO 9241-9 [11] standard are documented over time and used to determine the learnability of the devices. Importantly, this study also extends the previous work by deriving dependent measures of throughput and workload for the pointing devices in a wearable context. As described below, there have been very few studies that report throughput and workload values for input devices evaluated in a wearable context. The remainder of the chapter explores the relevant knowledge, followed by a description of the method and results of the study and presents a discussion of the findings.

6.2 Background

This study draws upon relevant knowledge from longitudinal evaluation, learnability, workload and Fitts' law evaluation of pointing devices. For an overview of longitudinal

evaluation, please refer to Section 2.4.4. With the exception of Hwang et al. [140] who evaluate a wrist mounted device consisting of an optical sensor and Horie et al. [142] who evaluate the placement of accelerometers on different body parts, (both described in Section 2.3.1), the wearable literature appears to be limited to the longitudinal evaluation of input devices performing text entry or examining text entry techniques only (see Section 2.5.4). It does not appear that the participants were required to don a wearable computer in either of the studies undertaken by Hwang et al. [140] and Horie et al. [142]. Participants wore a monocular head-worn display in the study undertaken by Horie et al. [142]. However, the display device used by Hwang et al. [140] was not described.

Typically, Fitts' law has been used to derive the dependent measure of throughput which allows comparisons between different devices across studies to be made (obtainable when throughput is calculated the same way). A detailed description of Fitts' law testing of pointing devices can be found in Section 2.4.2. The introduction of Fitts' law seems appropriate in this study as Fitts' law should be evaluated once learning has stabilised [13]. The longitudinal nature of this study enables the evaluation of Fitts' law following exposure to the devices over a number of days. Doing so provides a good measure of practiced performance.

Very few studies have evaluated the dependent measure of throughput for input devices in a wearable context. The aforementioned study undertaken by Hwang et al. [140] derives mean throughput values for the FeelTip (a novel input device) and for the comparative analogue joystick. However, the authors do not state how the measure of throughput is calculated and as previously stated, the display device used is also not described. Oakley et al. [5] derive a throughput value however the experimental conditions were presented on a 24 inch flat panel display. Hong et al. [217] explore the use of dynamic cursor gain control against normal gain control. In the wearable condition participants wore a Micro-Optical monocular head-worn display and used a Dolphin Mouse trackball. Although the authors derive throughput measures, throughput is calculated using the reciprocal of the slope of the regression line ($1/b$) instead of mean of means as recommended by Soukoreff and MacKenzie [13] and adhering to the ISO 9241-9 standard [11]. The work by Calvo et al. [143] appears to be one of the few studies that uses Fitts' law in a wearable context following the recommendations made by Soukoreff and Mackenzie [13] which support and supplement the ISO 9241-9 standard. However,

participants wore a small wearable computer on a tactical vest with the experimental conditions displayed on the small flip-down 5.6" screen. The study presented in this chapter appears to be the first to derive the dependent measure of throughput (adhering to the ISO 9241-9 standard and following the recommendations made by Soukoreff and Mackenzie [13]) for pointing devices evaluated while wearing a binocular optical see-through head-worn display and wearable computer.

Likewise, the subjective measure of workload has been measured in very few studies evaluating pointing devices in a wearable context. For an overview of workload, please refer to section 2.4.3. The study presented by Chamberlain and Kalawsky [10] evaluating a touch screen with stylus and off-table mouse and the series of studies undertaken by Chamberlain [214] evaluating three pointing devices, an off-table mouse, a track-pad and a stylus report workload ratings for the devices. However, participants were evaluated while wearing a computer housed in a vest with a fold down touch screen. This study appears to be the first to derive the subjective measure of workload for pointing devices evaluated when wearing a head-worn display and wearable computer.

In light of the above, the study presented in this dissertation appears to be the first to evaluate pointing devices in an extended study (over time) and to derive the dependent measures of throughput and workload while wearing a wearable computer and head-worn display (i.e. in a wearable context). The following section explores relevant knowledge in the area of learnability.

6.2.1 Learning and Performance

"People who assess learning must make inferences from observing performance during practice and tests." [229] This statement regarding the assessment of learning makes a distinction between performance from learning. Magill [229] defines performance as an observable behaviour that may be influenced by the existence of performance variables (for example: fatigue, anxiety, alertness, etc.). However learning is described by Magill [229] as "a change in the capability of a person to perform a skill that must be inferred from a relatively permanent improvement in performance as a result of practice or experience". This is echoed by Rose and Christina [230]; "whether motor learning has occurred or the extent to which it has occurred is inferred based on the extent of change that is directly observed in the learner's movement performance". Learning cannot be

directly observed because the learning process takes place within the learner [230]. Performance on the other hand, can be directly observed. The best way to assess learning is from the observation of peoples' performance [231]. We can observe the reliable changes in performance that may result from learning [230]. Performance measures can be documented over time and used to determine how far the learner has progressed [230]. Magill [229] identifies five performance characteristics as skill learning takes place:

- Improvement: the performance of a skill improves over time.
- Consistency: the performance becomes increasingly consistent. Typically, initial performance attempts are more variable than later attempts that become more consistent as learning progresses.
- Stability: the performance is less likely to be influenced by internal or external factors, such as stress, environment, etc.
- Persistence: the improved performance is permanent over time.
- Adaptability: the performance of the skill can be successfully applied to different circumstances.

There are many factors that may positively or negatively influence performance. Therefore, observable changes in performance do not always indicate that learning has occurred [230]. Factors that may have an effect on performance are fatigue, level of motivation, level of anxiety, and boredom to name a few. The existence of these factors may have an effect on the way a person performs, but may not be indicative of the amount of learning the person has achieved [229] or even that learning has occurred. Given that there are many factors that may temporary affect a person's performance, it is therefore appropriate to observe performance on several occasions in order to make inferences about a person's learning [230], [231]. Observing performance on several occasions makes it possible to determine whether the changes in performance are reliable and durable [230]. Changes in performance that are consistently repeated over time are considered reliable and evidence that learning has occurred [230]. The reliable changes must be the result of instruction, practice and/or training and not a result of the factors that may temporarily affect performance (such as motivation or fatigue) [231]. Retention tests are commonly used as a way to overcome the problem of factors that may temporarily influence performance during practice [229].

6.2.2 Retention Tests

The above definition of learning in Section 6.2.1 states that the improvement in performance should be relatively permanent. The permanent or persistence characteristic used to infer learning from performance, can be measured with a retention test. Retention tests may be used in order to provide information about the durability of the performance achieved in acquisition (practice) over time [230]. A retention test is performed after a period of non-use or of no practice called the retention interval [230]. The length of time between the end of practice and the test is not specified, however, one should ensure that it is of sufficient length to allow the influence of performance variables to dissipate [229]. The task used to assess performance in a retention test is the same task used in the acquisition phase. The retention test is used to determine "how much of the task proficiency gained during the acquisition was retained or, alternatively, how many trials were saved in relearning the task that was learned in the acquisition phase" [230]. One may therefore reasonably infer that learning has occurred if the performance achieved in acquisition is retained. Rose and Christina [230] state that retention tests are used to: determine whether the performance achieved in acquisition is retained in order to make inferences about how much learning was remembered or lost over a retention interval; and determine whether the performance is the result of variables that may be used to infer learning (such as instruction and practice). Retention tests are used to assess learning. As stated by Magill [229], "if a person's practice performance does represent learning, then that person's performance on a retention test should demonstrate the persistence characteristic and not deviate too much from his or her performance at the end of practice". In addition, if there is a significant improvement between the performance level on the first day of practice and that of the retention test, then the significant improvement is evidence that learning has occurred [229].

6.2.3 Performance Curves

Performance curves are the most common and widely used method for evaluating learning [229-231]. Performance curves graphically illustrate the level achieved on a performance measure for each time period, task, etc. and provide information regarding the rates of improvement during skill learning [229]. Typically, a learner experiences a large amount of improvement relatively quickly followed by small improvements as

practice continues. This change in the rate of improvement has been well documented in motor learning [229]. As described by Magill, Snoddy [229] termed this the power law of practice.

6.2.4 The Effects of Personal Differences on Learning

Individual differences may influence a person's performance and learning of a motor skill. Research into individual differences typically seeks to determine whether predictions can be made about how people will perform based on their abilities, or to ascertain the abilities that lead to differences in performance [231]. This approach to research is known as the differential approach and focuses on the characteristics that make people different from each other, that is, the factors that contribute to an individual's unique performance. The experimental approach on the other hand, focuses on the factors that influence people in the same way [231]. Schmidt and Wrisberg [231] list the individual difference factors that may contribute to differences in performance as being: abilities, attitudes, body type, cultural background, emotional makeup, fitness level, learning style, maturation level, motivational level, previous social experiences and previous movement experiences. Card et al. [232] identify the following individual user differences that effect performance: intellectual abilities, cognitive style, experience, knowledge and perceptual-motor skill. Abilities are defined as "stable, enduring traits that, for the most part, are genetically determined and that underlie a person's skill in a variety of tasks" [231]. People have different abilities and therefore differ in their levels of skill [231]. Researchers have identified as many as 20 to 30 cognitive and motor abilities [231], to name a few; manual dexterity, reaction time, etc.

The three stage model of Fitts and Posner as described by Magill [229] proposes that there are three stages associated with learning a motor skill; cognitive, associative and autonomous stages. Learners acquiring a new skill move from the initial cognitive stage through to the final autonomous stage [229]: during the cognitive stage, performance is variable, there are a large number of errors, and the focus is on cognitive problems; the associative stage produces fewer errors, with the learner focusing on successful skill performance with less variability; the final stage of learning is called the autonomous stage, where skill performance occurs without conscious thought and variability in performance is very small. Ackerman [233, 234] identifies three abilities that are involved

in each of the aforementioned stages of learning; the cognitive stage is dependent upon general ability, underlying the associative stage is perceptual speed ability, and the autonomous stage is dependent upon psychomotor abilities.

As individuals embark upon learning a task, questions about their learning process arise [235]; is their rate of learning more likely to be similar or different to that of others? Does practice increase the amount of variance between people, or decrease it? For simple and consistent tasks, Ackerman [233] states that the abilities that predict performance change during skill acquisition. While general intelligence abilities (verbal, spatial, math, etc.) are an important predictor of performance for novice learners, perceptual speed and psychomotor abilities appear to be better predictors of performance after extensive practice [236]. Consistent practice was found to reduce the inter-individual variance in performance and was also important in improving speed and accuracy performance [236]. Faster and slower learners should begin to converge in their performance [233, 234] during the autonomous stage since cognitive abilities are less likely to play a part in influencing performance in this stage. The differences in performance will therefore be dependent upon an individual's psychomotor abilities [233] during the autonomous stage. Evidence from research as stated by Robb [235], has found that the variation between individuals becomes greater given continued practice of a complex motor task.

Many studies have explored the effect personal differences may have on learning. User's experience, technical aptitudes, age and domain specific skills have been found to predict differences in computer based-skill, while personality and affective factors have not been found to be reliable predictors of performance [237]. Egan [237] states that experience is often the most powerful predictor of performance. Similarly, Shneiderman [238] acknowledges that background experience and knowledge in the task and interface domain play vital roles in learning and performance. Gomez et al. [239] evaluated novice users learning to use a text editor. The authors found that age and spatial memory were the best predictors of how well users learned to use a text editor. That is, participants who scored lower in a spatial memory test had greater difficulty learning to use a text editor and older people had more trouble than younger people.

Gugerty et al., [240] evaluated 180 participants required to locate information on the internet. The authors found that spatial and verbal ability influenced the speed and

accuracy by which they performed internet searches. Participants' attitudes towards computers were also found to influence speed and accuracy. Resulting from the comparison of 92 publications on the usability of hypertext systems, Nielsen [12] found that 4 of the 10 largest effects were due to individual differences between users, and two were due to task differences. As a result of the comparisons, the author concludes that the users' task and their individual characteristics and differences are the two most important issues for usability. Burton-Jones and Hubona [241] found that individual user differences have significant effects on the frequency and volume of usage behaviour.

Zudilova-Seinstra et al. [242] performed a user study to determine whether gender, age and computer experience affect the way people interact with 3D medical image data in a virtual environment using 2D and 3D input devices. The authors use a positioning and selection task for the study. Differences in gender, age and game experience were found to have an effect on peoples' performance and on subjective user preferences. For the positioning task, people with prior game experience and younger people were able to benefit from the virtual P5 glove in 3D mode. However, individual differences in the selection task were not able to guide the selection of input method/device. The authors found that 3D input was better suited to the positioning task where as 2D input was sufficient for the selection task.

Following a study involving 179 subjects performing a psychomotor task conforming to Fitts' law and a battery of twenty-five psychometric tests, Roberts [243] found no evidence of correlation between intelligence and mean time. In fact, Roberts [243] states that certain studies reporting correlation between movement time and intelligence should be viewed with suspicion.

6.2.5 Studies Evaluating Input Devices and Personal Differences

Mahmud and Kurniawan [244] present a study that evaluates older people performing browsing tasks and playing solitaire using a mouse, touch screen and tablet-with-stylus input devices. The authors use psychometric tests (Simple Reaction Time, Mini Mental State Exam and Identical Picture) to evaluate participants as well as the dependent measure of time (seconds). The authors conclude that some psychometric data was the best predictor of task performance. Results indicate that perceptual speed was the best predictor of task performance when using the mouse in both the browsing and game

tasks, followed by user experience. Motor speed and experience were also predictors of performance in certain combinations of task and input device. Results indicate that in several cases, users' perceptual speed was the best predictor of task performance.

Along with other studies that explore the effect of age on mouse usage [245, 246], Smith et al. [247] evaluate the effect of age on the performance of mouse control techniques. Participants were broken up into three age groups and performed four target acquisition tasks, pointing, clicking, double-clicking, and dragging. The authors also focus on measuring age-related changes in abilities such as abstraction, spatial ability, processing speed, visuo-motor ability, perceptual speed and motor coordination. Motor coordination was found to be the sole predictor of slip errors for clicking and double-clicking tasks. Older participants experienced more difficulties performing mouse tasks than younger participants. The more complex tasks of clicking and double-clicking revealed a correlation between performance and age.

There has been a great amount of research that has explored the relationship between abilities and skill acquisition, although, a strong, consistent correlation between the two has not been demonstrated [234]. However, the effect that individual differences have on performance and skill acquisition is difficult to ignore. While exploring differences in users may provide insights into design alternatives and identify cognitive factors that determine performance [248], this research approach is beyond the scope of the study presented in this chapter and perhaps will be an interesting consideration for future work. Instead, the study presented in this chapter employs an experimental approach that seeks to explore the factors that influence all people in the same way [231]. The study of abilities and skill acquisition may provide insights into the usability of devices, however, given the number of participants that would be needed and the large amount of time such testing would take, it therefore falls outside the scope the dissertation.

6.3 Experiment

The purpose of this study is to explore the performance of four pointing devices suitable for use with a wearable computer by way of an extended learnability study. The task performed by participants is target selection. Four commercial pointing devices are used (trackball (Section 2.3.3.1), gyroscopic mouse (Section 2.3.3.3), Twiddler2 mouse (Section 2.3.3.4)), and the touchpad (described in Section 2.3.3.2). A tabletop mouse was also

included as a benchmark for comparison with traditional desktop user interaction techniques.

The hypotheses of the study were as follows:

- H1: A participant improves with a device given repeated use/exposure over time (improvement).
- H2: There is a measurable difference between the time taken to see no more significant improvement between the different devices, and can therefore establish a ranking of the devices.
- H3: The improved device performance is permanent over time (persistence).
- H4: There is a measurable difference between the size and distance wheel combination presented to participants, and can therefore establish a ranking of wheel combinations. (Wheel combinations represent a target of a given size placed at a given distance apart, for example, wheel 16 x 500 represents a target that is 16 pixels in size and placed at a distance of 500 pixels apart).
- H5: A particular pointing device is better suited to a particular size and distance wheel combination.
- H6: Fitts' law applies to the use of pointing devices in a wearable context. There is a measurable difference in the pointing devices' Throughput (bps) value and can therefore establish a ranking between devices.
- H7: There is a measurable difference in workload when using the pointing devices and can therefore establish a ranking between devices.
- H8: Users have a preference for a particular pointing device.

6.3.1 Participants

Seventeen participants were recruited for the study. Participants were computer-literate students at the University of South Australia. There was one female and one left handed participant. Mean age was 23.6 years (SD 4.48). Participants were required to have normal corrected vision, were able to stand and walk; did not suffer from colour blindness, eye disease, eye injury, glaucoma, photosensitive epilepsy or seizures, and were able to wear a backpack of approximately five kilograms in weight. Novice participants were sought for the study. Participants were considered novices if they had not previously used the pointing devices in a wearable context. Given the time commitment required for the study, participants were compensated $100.00 for their

participation in all six sessions ($50.00 for completing all of the first five sessions and $50.00 for completing session six).

6.3.2 Equipment

The experiment was conducted on a HP Mini 210 Laptop running the Microsoft Windows 7 operating system. The output device was a Sony Glasstron optical see-through head-worn display with resolution 800×600 SVGA (FoV 30 degrees (h) x 22.5 degrees (v), 38 degrees diagonal). Four commercial pointing devices were used: trackball, gyroscopic mouse, Twiddler2 mouse and touchpad. A desktop mouse was also used as a benchmark. The HP Mini 210 laptop, wireless receiver for the gyroscopic mouse and power converter for the head-worn display, were attached to a small backpack and operated with battery power.

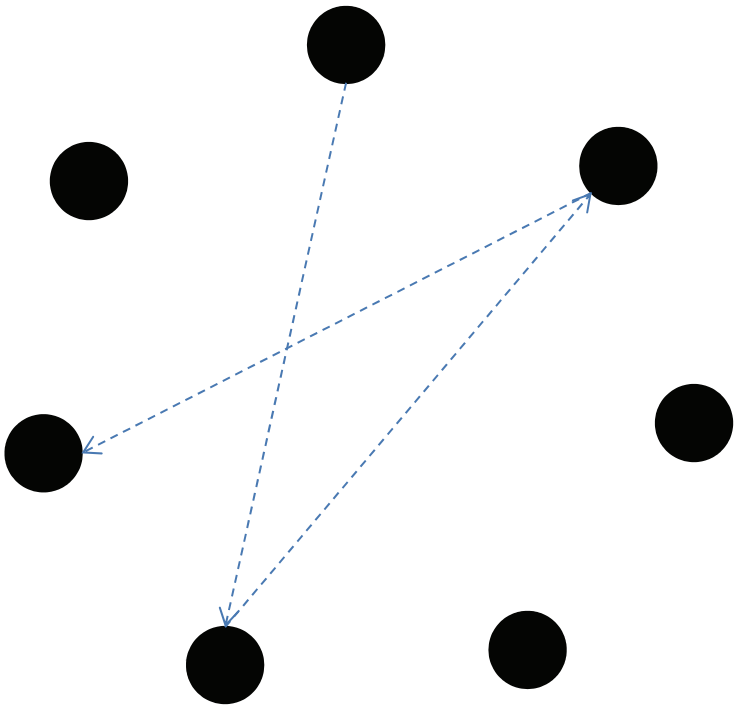


Figure 34: Experimental task illustrating the first three trials (learnability study)

6.3.3 Software and Data Collection

A custom built application written in Java coordinated the entire session of tasks. The task undertaken is based on the multi-tapping selection task as defined in the ISO 9241-9 [11, 13]. Seven yellow targets were positioned at a given distance, equally around the centre of the screen (indicating all possible target positions). The target to select was

highlighted blue. With each mouse click, the blue target moved to the next target. A trial began with a target selection and ended with the next target selection regardless of whether the target selection was hit or missed. If the target was hit, it changes back to yellow and the next blue target requiring selection is highlighted. If the target was missed, the target flashed red and the next blue target requiring selection was highlighted. There are seven trials per size and distance combination. The starting point was positioned on one of the seven destination targets. The sequence (circle of targets) was started when the participant selected the blue target and ended when the participant had selected all seven targets and was back at the starting point. Participants were required to sequentially select a blue target as quickly and accurately as possible. Figure 34 illustrates the sequence of the first three selections (marked by the dotted line between targets). For each circle of targets, seven trials were performed. An individual task presented 42 selections to the participant made up of seven selection trials per size (three) and distance (two) combination.

The data recorded for each task includes the times in nanoseconds at which the user attempted to select the start (blue) target and every selection, until and including the final selection. The total number of errors (missed target selections) and the total task time between the first selection and the final selection (42 trials) were also recorded. For use in Fitts' law [13] calculations, coordinates of mouse clicks are also recorded.

6.3.4 Design

The following independent variables (factors and levels) were examined:

Factor	Levels
Device	Gyroscopic mouse, touchpad mouse, trackball mouse, Twiddler2 mouse, desktop mouse (used as a benchmark)
Target Size	16 pixels, 32 pixels, 48 pixels
Target Distance	300 pixels, 500 pixels
Session	1, 2, 3, 4, 5, 6

The dependent variables were as follows:

Dependent Measures	Explanation
Total task time	The total amount of time (seconds) taken from the first selection up to and including the final selection (42 trials).
Number of errors	The total number of errors defined as missed target selections.
Trial completion time	The time taken (seconds) to select a target followed by the next target selection regardless of whether the target selection was hit or missed (i.e. time taken in seconds for one trial). Also referred to as movement time.
Throughput (bps)	Measure that combines both the speed and accuracy of participants' performance. Calculated as described by equations 5, 6 and 7 in Section 2.4.2.
Workload	Subjective workload measure experienced while using the pointing devices. Assessed using the NASA TLX assessment of workload. Calculated as described in Section 2.4.3.

The experiment was a $5\ (device) \times 3\ (target\ size) \times 2\ (distance)\ \times 6\ (session)$ repeated-measures design, meaning that all participants were tested on all experimental conditions. The study is similar to previous research designed to assess input devices via a longitudinal design [140, 142, 199, 201]. The study explores the use of the pointing devices over a period of time.

Participants were required to undertake a total of six sessions over six days prescribed as follows; the first five sessions were scheduled Monday through Friday on consecutive days at approximately the same time each day (constrained by the rule that sessions were to be separated by no less than 12 hours and no more than 48 hours). The sixth session assessed learning by a retention task and was scheduled at least four days and no more than seven days after the fifth session. This was determined to be sufficiently long enough to allow the influence of any performance variables to dissipate [229]. Each session consisted of five blocks of trials. Each block contained five tasks, one task for each pointing device. Each task within a block used a different pointing device allocated in random order. An individual task presented 42 trials to the participant made up of 7 selection trials per size (16 pixels, 32 pixels, 48 pixels) and distance (300 pixels, 500 pixels) combination presented in random order. The target sizes were chosen as they represent typical icon sizes used by Microsoft and are in keeping with the previous experiment (drag and drop described in chapter 4). Participants completed five tasks with each pointing device per session totalling 25 tasks for each session with the constraint that there was an

equal number of participants who operated each pointing device as the first device of a session.

6.3.5 Procedure

In the first session, the supervisor, reading from a script, explained to each participant what was expected of them during the sessions. Participants were required to read and information sheet, fill out a consent form, and undergo a short training session using the pointing devices. The supervisor demonstrated how each pointing device was operated prior to the training. Participants were instructed to use the devices with their dominant hand and to select the targets as quickly and accurately as possible. The supervisor then started the custom-built application. The application provided prompts that instructed the participant which device to use in order to complete each task (42 trials). Participants completed one task per pointing device. As the purpose of the training session was to familiarise participants with the pointing devices, the participants sat in a chair using the laptop computer on a desk in order to perform the training. Following the training, participants were instructed to start the experimental session lasting approximately one hour. Participants were required to don a wearable computer and complete the tasks while stationary.

Twelve stations were positioned along the walls of a quiet, straight hallway, designated by paper posters on the wall. The application prompted the participants to walk to the next indicated station, which provided instructions regarding which pointing device to use for the task. The stations were addressed more than once. Participants remained stationary while completing the task. Participants were given the option of resting for a few minutes after completing each block of tasks, however, participants were required to rest for at least five minutes after having completed the second and fourth blocks of tasks.

In sessions two through six, the supervisor, if necessary reminded the participant how each device worked and allowed the participant to familiarise themselves with the devices before starting the experimental session. Each session had the same experimental procedure (excluding the training) as session one.

At the end of each session, participants were required to fill out a range of questionnaires. All sessions took approximately 1 hour to complete with the exception of the first and fifth sessions taking approximately 1.5 hours to complete due to the training involved and the questionnaires to be completed.

6.4 Quantitative Results

This section describes the quantitative results of the experiment. Unless otherwise stated, Analysis of Variance (ANOVA) models were used in order to determine significance. Mauchly's test was used to determine whether sphericity had been violated. Degrees of freedom were corrected using Greenhouse-Geisser estimates where sphericity had been violated. A Bonferroni correction was employed for all *post hoc* analysis. Statistical significance is set at α = 0.05.

6.4.1 Adjustment of Data and Analysis

Spatial outliers were removed from the data (0.28% of data points were removed from the analysis). Spatial outliers are defined as (a) selections where the coordinates fell outside of the current target and (b) the distance moved after the previous click was less than half the distance ($A/2$) or the distance to the centre of the current target was larger than two times the width of the target ($2W$) [14, 181, 249, 250]. Time or error values greater than three standard deviations away from the mean were also removed from the data. In light of the above, the following analysis was performed on 15 participants.

6.4.2 Total Task Completion Time and Performance Curves

Across all devices (excluding the table-top mouse) and sessions, the mean total time for one task (42 trials) was 76.31 seconds (SD 12.59). A 4 (device) x 6 (session) ANOVA was conducted on the measure of task time. The analysis revealed that there was significant effect of device $F_{(3,42)}$ = 11.383, $p < 0.05$ and session $F_{(5,70)}$ = 43.787, $p < 0.05$ on task time. There was a significant interaction between device and session $F_{(15,210)}$ = 2.772, $p < 0.05$. Participants' performance improved with the devices over the course of the six sessions. Across all devices, Helmert contrasts reveal no significant difference from session 4 onwards. Across all sessions, pairwise comparisons revealed a significant difference between the following devices; gyroscopic mouse and touchpad mouse,

touchpad mouse and Twiddler2 mouse, and trackball mouse and Twiddler2 mouse. Figure 35 illustrates the mean total task time for all devices over all sessions.

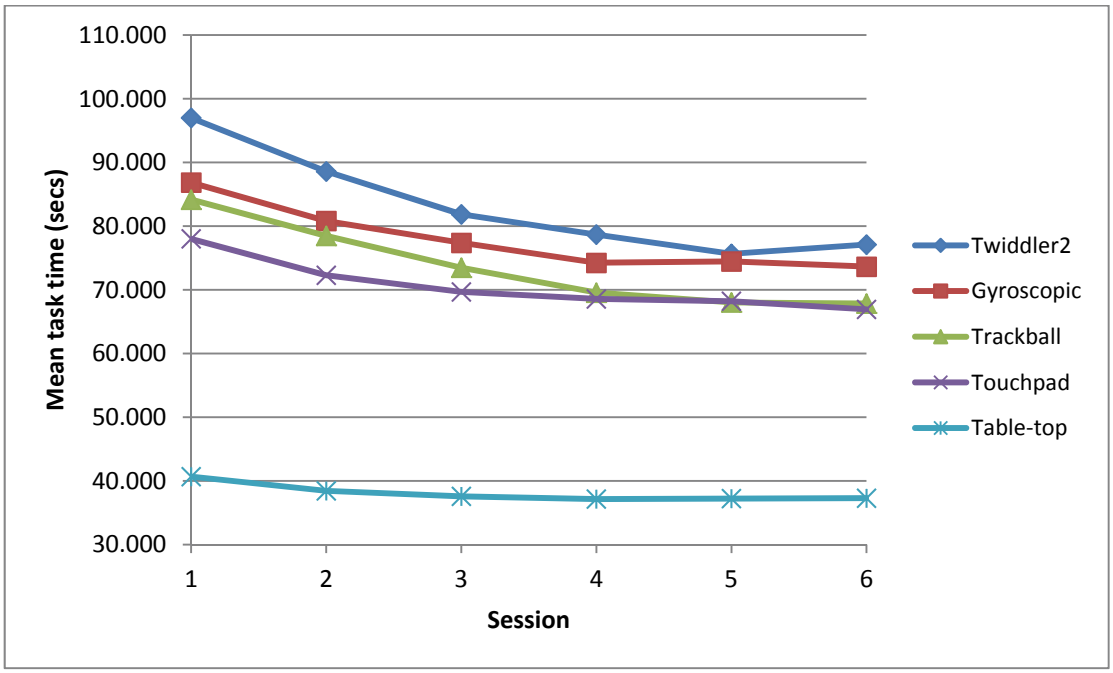


Figure 35: Device mean total task time over all sessions (learnability study)

Table 22: Mean total task time by device and session (secs). Std. dev. in parenthesis (learnability study)

	Pointing Device				
Session	**Table-top mouse**	**Touchpad**	**Trackball**	**Gyroscopic**	**Twiddler2**
1	**40.67 (3.71)**	**77.99 (10.55)**	**84.17 (8.33)**	**86.84 (15.41)**	**97.00 (14.95)**
2	38.43 (2.50)	72.28 (7.55)	78.48 (8.13)	80.81 (12.39)	88.59 (12.46)
3	37.57 (3.49)	69.67 (8.95)	73.48 (8.91)	77.38 (10.88)	81.85 (12.22)
4	37.15 (3.23)	68.57 (8.34)	69.57 (6.87)	74.24 (10.86)	78.67 (10.13)
5	**37.22 (2.98)**	**68.19 (9.61)**	**68.02 (7.21)**	**74.46 (13.58)**	**75.65 (11.17)**
6	37.29 (3.09)	66.92 (9.39)	67.85 (6.20)	73.63 (10.90)	77.11 (11.60)
Mean	38.06 (3.34)	70.60 (9.60)	73.59 (9.58)	77.89 (12.99)	83.15 (14.02)
Improvement (Session 1-5)	**8.48%**	**12.56%**	**19.18%**	**14.26%**	**22.01%**

The mean task time for session one is 86.84 seconds for the gyroscopic mouse, improving to 74.46 for session five. The mean time for session one for the touchpad is 77.99 seconds which improved to 68.19 at session five. The trackball recorded a mean time of

84.17 seconds for session one improving to 68.02 in session five. The Twiddler2 recorded a mean time of 97.00 seconds in session one improving to 75.65 by session five. The mean time for the table-top mouse was 40.67 seconds in session one improving to 37.22 by session 5. Table 22 lists the mean task time for every device over all sessions.

Table-top mouse

The table-top mouse was included as a benchmark. At session 5, the trackball performs closest to the table-top mouse but is still 82.75% slower. The touchpad is 83.20% slower, the gyroscopic mouse is 100.04% slower and the Twiddler2 is 103.24% slower than the table-top mouse.

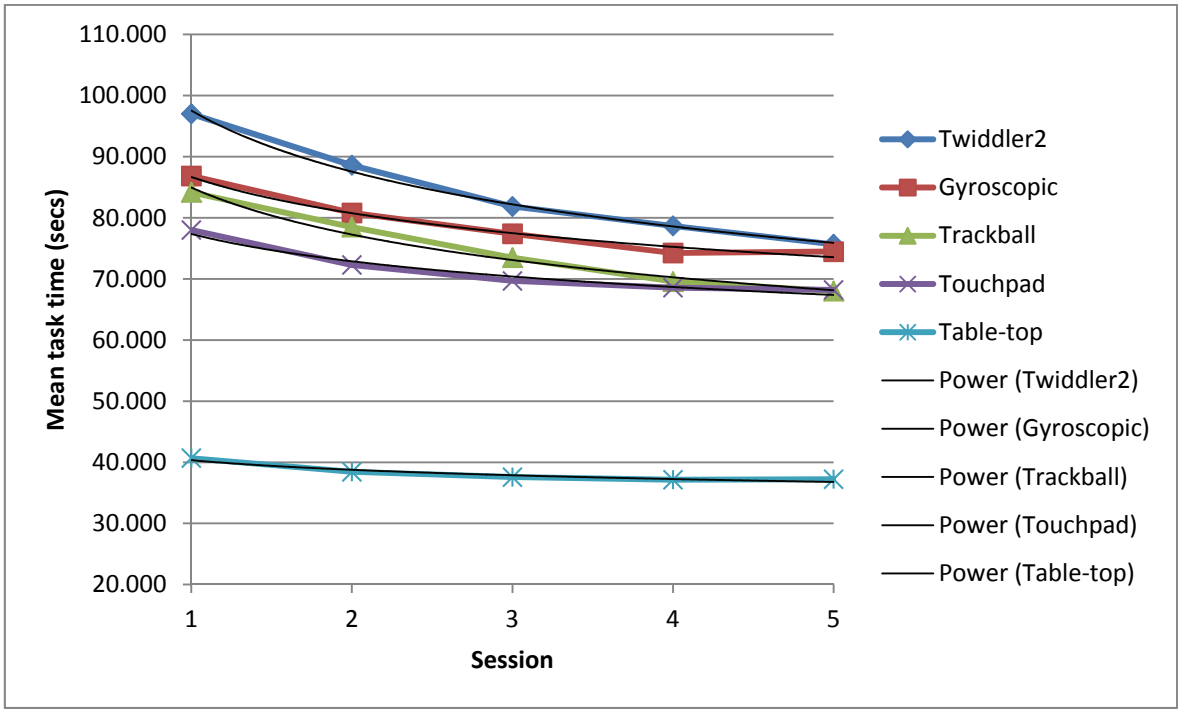


Figure 36: Performance and regression curves for five sessions (learnability study)

Regression curves (Figure 36) were derived for each device over the five sessions in order to model the power law of practice [232]. The equations for the curves are as follows:

Twiddler2: $y = 97.541x^{-0.156}$, $R^2 = 0.9949$

Gyroscopic: $y = 86.674x^{-0.102}$, $R^2 = 0.9802$

Trackball: $y = 84.951x^{-0.137}$, $R^2 = 0.985$

Touchpad: $y = 77.35x^{-0.086}$, $R^2 = 0.968$

Table-top mouse: $y = 40.347x^{-0.057}$, $R^2 = 0.9376$

The x values represent the number of sessions and the y values represent the predicted mean task time in seconds for a session. The curves for the four devices (Twiddler2, Gyroscopic, trackball and Touchpad) have R^2 values greater than 96% indicating that they fit the data well. The model results in a significantly good degree of prediction of the outcome variable (mean task time) accounting for over 96% of the variance. The values of R^2 indicate that session can account for over 96% of the variation in mean total task time. The models can explain over 96% of the variation. The Twiddler2, trackball and gyroscopic mouse show a greater improvement with practice than the touchpad and table-top mouse. The touchpad and table-top mouse demonstrate very little improvement with practice.

6.4.2.1 Device Performance Improvements (Time)

The amount of time taken to see no more significant improvement over the six sessions and between the devices is determined using Helmert contrasts and outlined in Table 23.

Table 23: Device performance time (seconds) over six sessions (learnability study)

Device	Mean total task time across six sessions:	Significant effect of session on mean total task time:	Helmert contrasts reveal no significant difference from:
Table-top mouse	38.06 (3.34)	$F_{(5,70)} = 14.458, p < 0.05$	Session 3 onwards
Gyroscopic	77.89 (12.99)	$F_{(5,70)} = 7.065, p < 0.05$	Session 3 onwards
Touchpad	70.604 (9.60)	$F_{(5,70)} = 42.513, p < 0.05$	Session 4 onwards
Trackball	73.595 (9.58)	$F_{(3.09,43.19)} = 27.764, p < 0.05$	Session 4 onwards
Twiddler2	83.145 (14.02)	$F_{(5,70)} = 42.709, p < 0.05$	Session 5 onwards

6.4.2.2 Differences Between Devices Over Six Sessions (Time)

Each session was analysed separately in order to determine whether there was a significant difference between the devices in each session. For each session, there was a significant effect of device on total task time; pairwise comparisons revealed a significant difference between the devices. Table 24 outlines the difference between the devices for each session.

Table 24: Difference between devices (time) for each session. Std. dev. in parenthesis (learnability study)

Session	Device	Mean (secs)	Significant effect	Post hoc comparisons
Session 1	Touchpad	77.99 (10.55)	$F_{(3,42)} = 11.133, p < 0.05$	touchpad and trackball; touchpad and Twiddler2; trackball and Twiddler2
	Trackball	84.17 (8.33)		
	Gyroscopic	86.84 (15.41)		
	Twiddler2	97.00 (14.95)		
Session 2	Touchpad	72.28 (7.55)	$F_{(3,42)} = 13.359, p < 0.05$	gyroscopic and Twiddler2; touchpad and Twiddler2; trackball and Twiddler2
	Trackball	78.48 (8.13)		
	Gyroscopic	80.81 (12.39)		
	Twiddler2	88.59 (12.46)		
Session 3	Touchpad	69.67 (8.95)	$F_{(3,42)} = 8.601, p < 0.05$	touchpad and Twiddler2; trackball and Twiddler2
	Trackball	73.48 (8.91)		
	Gyroscopic	77.38 (10.88)		
	Twiddler2	81.85 (12.22)		
Session 4	Touchpad	68.57 (8.34)	$F_{(3,42)} = 7.748, p < 0.05$	touchpad and Twiddler2; trackball and Twiddler2
	Trackball	69.57 (6.87)		
	Gyroscopic	74.24 (10.86)		
	Twiddler2	78.67 (10.13)		
Session 5	Trackball	68.02 (7.21)	$F_{(3,42)} = 3.803, p < 0.05$	*No difference in pair-wise comparisons identified.*
	Touchpad	68.19 (9.61)		
	Gyroscopic	74.46 (13.58)		
	Twiddler2	75.65 (11.17)		
Session 6	Touchpad	66.92 (9.39)	$F_{(1.95,27.33)} = 7.668, p < 0.05$	gyroscopic and Touchpad; touchpad and Twiddler2; trackball and Twiddler2
	Trackball	67.85 (6.20)		
	Gyroscopic	73.63 (10.90)		
	Twiddler2	77.11 (11.60)		

6.4.3 Total Task Error Rate

Across all devices (excluding the table-top mouse) and sessions, the mean error rate for one task (42 trials) was 1.84 (SD 1.99). A 4 (device) x 6 (session) ANOVA on the measure of error rate was conducted. Analysis revealed a significant effect of device on error rate $F_{(1.184,16.582)} = 32.372$, $p < 0.05$. There was no significant effect of session on error rate or a device by session interaction. Across all sessions, pairwise comparisons revealed a significant difference between all the devices except for the; touchpad and trackball and touchpad and Twiddler2. Figure 37 illustrates the mean error rate for all devices over all sessions.

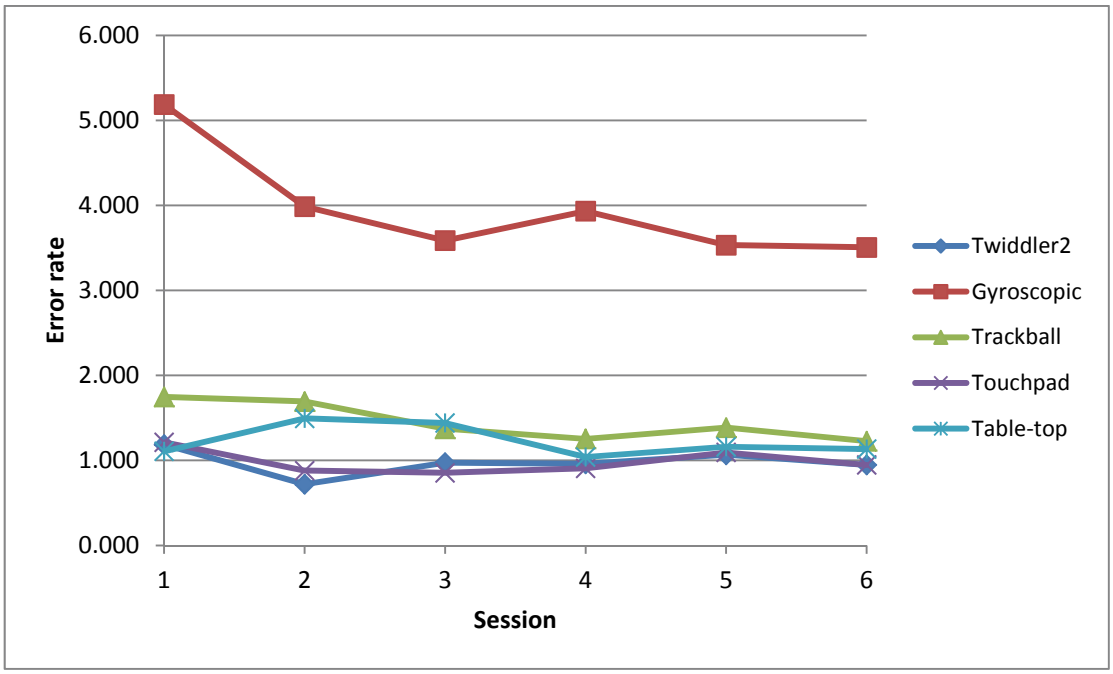


Figure 37: Device mean error rate over all sessions (learnability study)

The error rate for session one is 5.19 for the gyroscopic mouse, improving to 3.53 for session five. The error rate for session one for the touchpad is 1.21 which improved to 1.09 at session five. The trackball recorded a mean error rate 1.75 for session one improving to 1.39 in session five. The Twiddler2 recorded a mean error rate of 1.19 in session one improving to 1.07 by session five. The mean error rate for the table-top mouse was 1.11 in session one improving to 1.16 by session 5. Table 25 lists the mean error rate for every device over all sessions.

Table 25: Mean total error rate by device and session. Std. dev. in parenthesis (learnability study)

	Pointing Device				
Session	**Table-top mouse**	**Touchpad**	**Twiddler2**	**Trackball**	**Gyroscopic**
1	**1.11 (0.86)**	**1.21 (1.19)**	**1.19 (0.95)**	**1.75 (1.17)**	**5.19 (3.20)**
2	1.49 (1.13)	0.88 (0.49)	0.72 (0.58)	1.69 (1.20)	3.99 (2.68)
3	1.44 (1.37)	0.85 (0.76)	0.97 (0.89)	1.37 (1.11)	3.59 (2.12)
4	1.04 (0.75)	0.91 (0.91)	0.96 (0.72)	1.25 (1.26)	3.93 (2.35)
5	**1.16 (0.88)**	**1.09 (0.88)**	**1.07 (1.00)**	**1.39 (1.22)**	**3.53 (2.26)**
6	1.13 (0.92)	0.95 (0.81)	0.95 (1.21)	1.23 (1.12)	3.51 (3.02)
Mean	1.23 (0.99)	0.98 (0.85)	0.98 (0.90)	1.45 (1.16)	3.96 (2.63)
Improvement (Session 1-5)	**-4.82%**	**9.89%**	**10.11%**	**20.61%**	**31.88%**

Table-top mouse

At session 5, the percentage difference between the table-top mouse and other devices was calculated. Interestingly, the touchpad performed with 5.75% fewer errors and the Twiddler2 performed with 8.05% fewer errors than the table-top mouse. The trackball performed with 19.54% more errors and the gyroscopic mouse performed with 204.60% more errors than the table-top mouse.

6.4.3.1 Device Performance Improvements (Error Rate)

Across all six sessions for each device, session did not significantly effect error rate.

6.4.3.2 Differences Between Devices Over Six Sessions (Error Rate)

Each session was analysed separately in order to determine whether there was a significant difference between the devices in each session. For each session, there was a significant effect of device on error rate; pairwise comparisons revealed a significant difference between the devices. Table 26 outlines the difference between the devices for each session.

Table 26: Difference between devices (error) for each session (learnability study)

Session	Device	Mean	Significant effect	Post hoc comparisons
Session 1	Twiddler2	1.19 (0.95)	$F_{(1.335,18.695)} = 23.979, p < 0.05$	gyroscopic and touchpad; gyroscopic and trackball; gyroscopic and Twiddler2
	Touchpad	1.21 (1.19)		
	Trackball	1.75 (1.17)		
	Gyroscopic	5.19 (3.20)		
Session 2	Twiddler2	0.72 (0.58)	$F_{(1.367,19.135)} = 16.787, p < 0.05$	gyroscopic and touchpad; gyroscopic and trackball; gyroscopic and Twiddler2; trackball and Twiddler2
	Touchpad	0.88 (0.49)		
	Trackball	1.69 (1.20)		
	Gyroscopic	3.99 (2.68)		
Session 3	Touchpad	0.85 (0.76)	$F_{(1.175,16.446)} = 21.245, p < 0.05$	gyroscopic and touchpad; gyroscopic and trackball; gyroscopic and Twiddler2; touchpad and trackball
	Twiddler2	0.97 (0.89)		
	Trackball	1.37 (1.11)		
	Gyroscopic	3.59 (2.12)		
Session 4	Touchpad	0.91 (0.91)	$F_{(1.405,19.664)} = 26.458, p < 0.05$	gyroscopic and touchpad; gyroscopic and trackball; gyroscopic and Twiddler2
	Twiddler2	0.96 (0.72)		
	Trackball	1.25 (1.26)		
	Gyroscopic	3.93 (2.35)		
Session 5	Twiddler2	1.07 (1.00)	$F_{(1.445,20.226)} = 21.665, p < 0.05$	gyroscopic and touchpad; gyroscopic and trackball; gyroscopic and Twiddler2
	Touchpad	1.09 (0.88)		
	Trackball	1.39 (1.22)		
	Gyroscopic	3.53 (2.26)		
Session 6	Twiddler2	0.95 (1.21)	$F_{(1.351,18.915)} = 11.617, p < 0.05$	gyroscopic and touchpad; gyroscopic and trackball; gyroscopic and Twiddler2
	Touchpad	0.95 (0.81)		
	Trackball	1.23 (1.12)		
	Gyroscopic	3.51 (3.02)		

6.4.4 Trial Completion Time (Wheel Movement Time)

Across all devices (excluding the table-top mouse), wheels (size and distance combinations) and sessions, the mean trial movement time (one trial) was 1.82 seconds (SD 0.51). A 6 (session) x 4 (device) x 6 (wheel) ANOVA was conducted on the measure of mean movement time (one trial). The analysis revealed that there was significant effect of session $F_{(5,70)} = 45.238$, $p < 0.05$, device $F_{(3,42)} = 10.750$, $p < 0.05$, and wheel $F_{(1.272,17.807)} = 499.447$, $p < 0.05$ on movement time. There was a significant interaction between session and device $F_{(15,210)} = 2.602$, $p < 0.05$, session and wheel $F_{(5.997,83.958)} = 8.346$, $p < 0.05$ and device and wheel $F_{(3.669,51.360)} = 38.208$, $p < 0.05$. There was no significant interaction between session x device x wheel. Figure 38 illustrates the mean

trial movement time (one trial) achieved with all pointing devices for all sessions. Figure 39 shows the mean trial movement time (one trial) for all sessions for each of the wheel (size and distance) combinations.

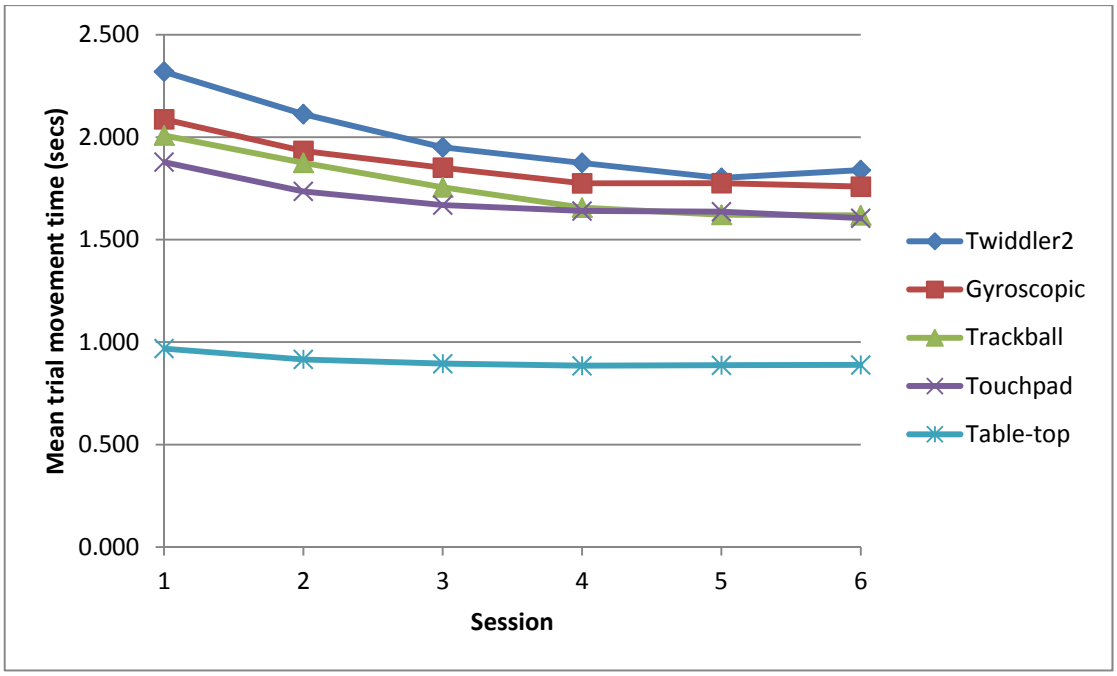


Figure 38: Mean trial movement time (seconds) for all sessions (learnability study)

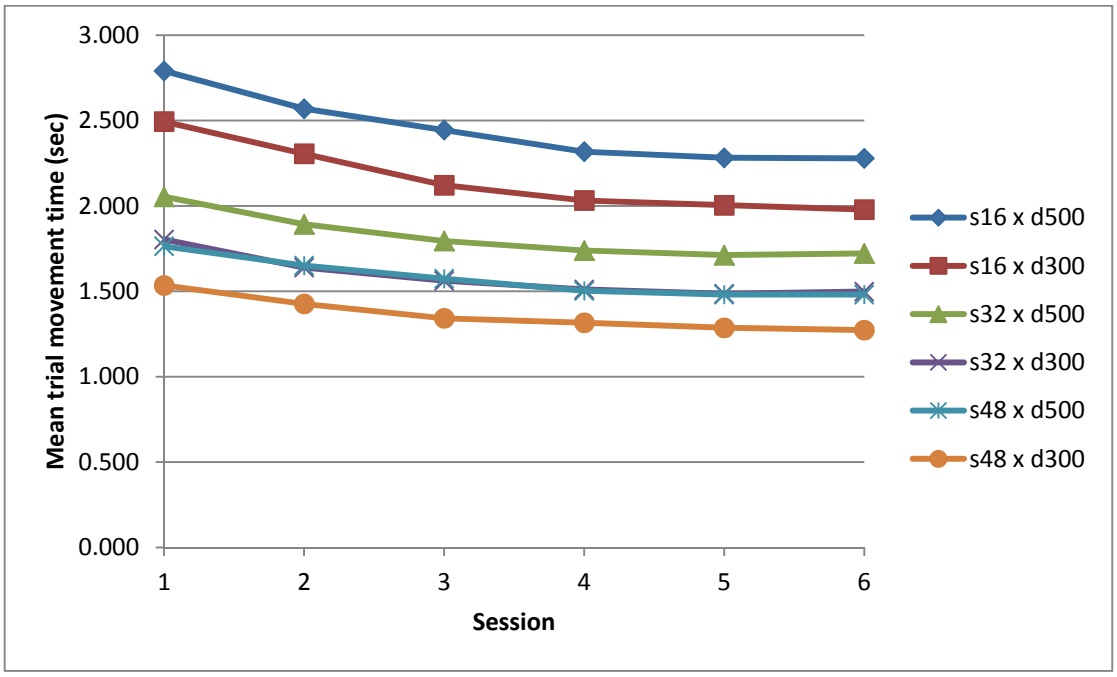


Figure 39: Mean trial movement time (seconds) for each wheel (size x distance) combination for all sessions (learnability study)

Across all devices and trial conditions, Helmert contrasts reveal no significant difference from session 4 onwards. Across all sessions and trial conditions, pairwise comparisons revealed a significant difference between the following devices; gyroscopic mouse and touchpad mouse, touchpad mouse and Twiddler2 mouse, and trackball mouse and Twiddler2 mouse. Table 27 lists the mean trial movement time per device across all sessions. Across all sessions and devices, pairwise comparisons revealed a significant difference between all trial conditions (size and distance combinations) except for wheel combinations of 32 pixels x 300 pixels and 48 pixels x 500 pixels. Table 28 lists the mean trial movement time per wheel (size and distance) combinations across all sessions.

Table 27: Mean trial movement time (seconds) per device across all sessions (learnability study)

Device	Mean (secs)	Std. dev.
Table-top mouse	0.91	0.08
Touchpad	1.69	0.24
Trackball	1.76	0.23
Gyroscopic	1.86	0.31
Twiddler2	1.98	0.34

Table 28: Mean trial movement time (seconds) per wheel (size x distance) combination across all sessions. Target sizes are 16, 32 and 48 pixels and distances are 300 and 500 pixels, i.e. wheel 16 x 500 represents a target size of 16 pixels placed at 500 pixels apart (learnability study)

Wheel	Mean (secs)	Std. dev.
16 x 300	2.16	0.44
16 x 500	2.45	0.48
32 x 300	1.58	0.29
32 x 500	1.82	0.30
48 x 300	1.36	0.24
48 x 500	1.58	0.26

Session Five and Session Six Analysis (Movement Time)

Across all devices (excluding the table-top mouse) and wheels (size and distance combinations) the mean trial movement time (one trial) for session five was 1.71 seconds (SD 0.45). A 4 (device) x 6 (wheel) ANOVA was conducted on the measure of mean movement time (for one trial) for session five data. The analysis revealed that there was significant effect of device $F_{(3,42)} = 3.585$, $p < 0.05$, and wheel $F_{(1.608,22.506)} = 255.421$, $p < 0.05$ on movement time. There was a significant interaction between device and wheel $F_{(4.029,56.410)} = 12.812$, $p < 0.05$. Pairwise comparisons of device did not reveal significant

results. Pairwise comparison of wheel revealed significant results between all comparisons excluding wheel combinations of 32 pixels x 300 pixels and 48 pixels x 500 pixels. Table 29 lists the mean movement time (seconds) for device and wheel (size and distance) combinations for session five.

Across all devices (excluding the table-top mouse) and wheels (size and distance combinations) the mean trial movement time (one trial) for session six was 1.71 seconds (SD 0.44). A 4 (device) x 6 (wheel) ANOVA was conducted on the measure of mean movement time (for one trial) for session six data. Analysis revealed that there was significant effect of device $F_{(1.98,27.74)}$ = 7.18, $p < 0.05$, and wheel $F_{(1.67,23.42)}$ = 264.54, $p < 0.05$ on movement time. There was a significant interaction between device and wheel $F_{(4.39,61.47)}$ = 12.17, $p < 0.05$. Pairwise comparisons of device revealed significant results between the gyroscopic and the touchpad and the trackball and the Twiddler2 devices. Pairwise comparison of wheel revealed significant results between all comparisons excluding wheel combinations of 32 pixels x 300 pixels and 48 pixels x 500 pixels. Table 29 lists the mean movement time (seconds) for device and wheel (size and distance) combinations for session six.

Table 29: Session five and session six mean device and wheel movement time. Target sizes are 16, 32 and 48 pixels and distances are 300 and 500 pixels, i.e. wheel 16 x 500 represents a target size of 16 pixels placed at 500 pixels apart. Std. dev. in parenthesis (learnability study)

	Mean movement time (secs)	
Device	**Session Five**	**Session Six**
Table-top mouse	0.89 (0.17)	0.89 (0.17)
Trackball	1.62 (0.40)	1.62 (0.39)
Touchpad	1.64 (0.37)	1.60 (0.35)
Gyroscopic	1.78 (0.60)	1.76 (0.55)
Twiddler2	1.80 (0.39)	1.84 (0.41)
Wheel	**Session Five**	**Session Six**
48 x 300	1.29 (0.23)	1.27 (0.19)
48 x 500	1.48 (0.21)	1.48 (0.21)
32 x 300	1.49 (0.23)	1.50 (0.24)
32 x 500	1.71 (0.26)	1.72 (0.26)
16 x 300	2.00 (0.39)	1.98 (0.35)
16 x 500	2.28 (0.42)	2.28 (0.41)

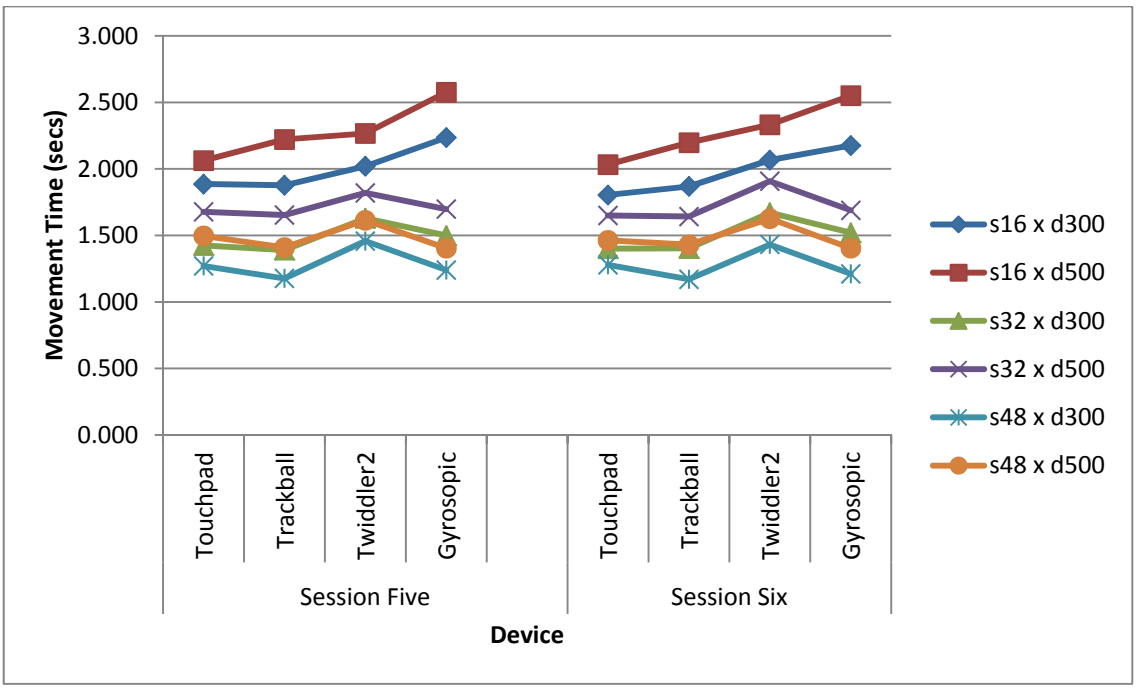


Figure 40: Device and wheel interaction for movement time - sessions five and six (learnability study)

As evidenced from Table 29 and Figure 40, it takes longer to complete a task as the difficulty of the task increases [175], that is either by decreasing the size of the target and/or increasing the distance between the targets. Targets that are larger and are closer together can be selected faster than targets that are smaller and further away from each other. Target sizes of 16 pixels placed at a distance of 500 pixels apart are selected significantly slower than any other combination.

6.4.4.1 Differences Between Devices for Wheel Combinations (Time)

Each wheel (size and distance) combination was analysed separately in order to determine whether there was a significant difference between the devices for sessions five and six. For each wheel combination in sessions five and six, there was a significant effect of device on mean trial movement time; pairwise comparisons revealed a significant difference between the devices. Table 30 outlines the difference between the devices for each wheel combination.

Table 30: Difference between devices for each wheel (size x distance) combination - time (sessions five and six). Std. dev. in parenthesis (learnability study)

Wheel	Device	Mean (secs) (Session Five)	Mean (secs) (Session Six)	Significant effect and post hoc comparisons
16 x 300	Trackball	1.88 (0.22)	1.87 (0.23)	Session 5: $F_{(3,42)} = 5.438$, $p < 0.05$ No pair-wise significance Session 6: $F_{(1.829,25.607)} = 9.458$, $p < 0.05$ gyroscopic and touchpad; touchpad and Twiddler2; trackball and Twiddler2
	Touchpad	1.89 (0.32)	1.80 (0.31)	
	Twiddler2	2.02 (0.28)	2.07 (0.32)	
	Gyroscopic	2.24 (0.55)	2.18 (0.41)	
16 x 500	Touchpad	2.06 (0.37)	2.03 (0.31)	Session 5: $F_{(3,42)} = 8.320$, $p < 0.05$ gyroscopic and touchpad; gyroscopic and trackball Session 6: $F_{(2.185,30.590)} = 8.584$, $p < 0.05$; gyroscopic and touchpad; gyroscopic and trackball
	Trackball	2.22 (0.33)	2.20 (0.29)	
	Twiddler2	2.27 (0.33)	2.33 (0.39)	
	Gyroscopic	2.58 (0.50)	2.55 (0.48)	
32 x 300	Trackball	1.39 (0.17)	1.40 (0.13)	Session 5: $F_{(2.180,30.521)} = 5.325$, $p < 0.05$ trackball and Twiddler2 Session 6: $F_{(3,42)} = 9.419$, $p < 0.05$; touchpad and Twiddler2; trackball and Twiddler2
	Touchpad	1.43 (0.17)	1.40 (0.21)	
	Gyroscopic	1.50 (0.27)	1.52 (0.24)	
	Twiddler2	1.63 (0.26)	1.67 (0.27)	
32 x 500	Trackball	1.65 (0.20)	1.64 (0.18)	Session 5: No significant difference. Session 6: $F_{(3,42)} = 7.762$, $p < 0.05$; touchpad and Twiddler2; trackball and Twiddler2
	Touchpad	1.68 (0.24)	1.65 (0.24)	
	Gyroscopic	1.70 (0.29)	1.69 (0.26)	
	Twiddler2	1.82 (0.29)	1.91 (0.27)	
48 x 300	Trackball	1.18 (0.13)	1.17 (0.13)	Session 5: $F_{(3,42)} = 7.546$, $p < 0.05$ gyroscopic and Twiddler2; trackball and Twiddler2 Session 6: $F_{(3,42)} = 11.569$, $p < 0.05$ gyroscopic and Twiddler2; trackball and Twiddler2
	Gyroscopic	1.24 (0.24)	1.21 (0.13)	
	Touchpad	1.27 (0.18)	1.28 (0.18)	
	Twiddler2	1.46 (0.28)	1.43 (0.21)	
48 x 500	Gyroscopic	1.40 (0.22)	1.40 (0.17)	Session 5: $F_{(3,42)} = 4.725$, $p < 0.05$ gyroscopic and Twiddler2; trackball and Twiddler2 Session 6: $F_{(1.656,23.183)} = 5.950$, $p < 0.05$; gyroscopic and Twiddler2
	Trackball	1.41 (0.13)	1.43 (0.15)	
	Touchpad	1.50 (0.20)	1.46 (0.20)	
	Twiddler2	1.61 (0.23)	1.63 (0.26)	

6.4.5 Trial Error Rate (Wheel)

Across all devices (excluding the table-top mouse), wheels (size and distance combinations) and sessions, the mean error rate (one trial) was 0.31 (SD 0.46).

A 6 (session) x 4 (device) x 6 (wheel) ANOVA was conducted on the measure of mean error rate (one trial). The analysis revealed that there was significant effect device $F_{(1.184,16.582)}$ = 32.372, $p < 0.05$, and wheel $F_{(1.552,21.735)}$ = 28.107, $p < 0.05$ on error rate. There was a significant interaction between device and wheel $F_{(2.696,37.748)}$ = 14.404, $p < 0.05$. Session did not significantly affect error rate. Interactions of session and device, and session and wheel reported no significant effect on error rate. There was no significant interaction between session x device x wheel. Figure 41 shows the error rate (one trial) for all sessions for each of the wheel (size and distance) combinations. Figure 42 illustrates the mean error rate (one trial) achieved with all pointing devices for all sessions.

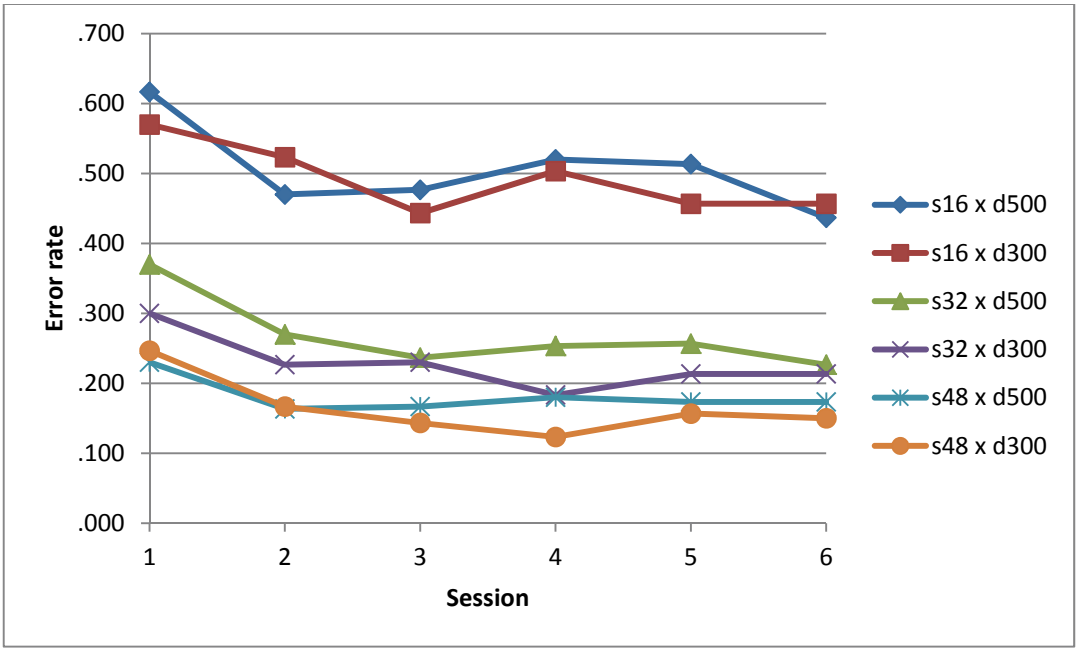


Figure 41: Mean error rate for each wheel (size x distance) for all sessions (learnability study)

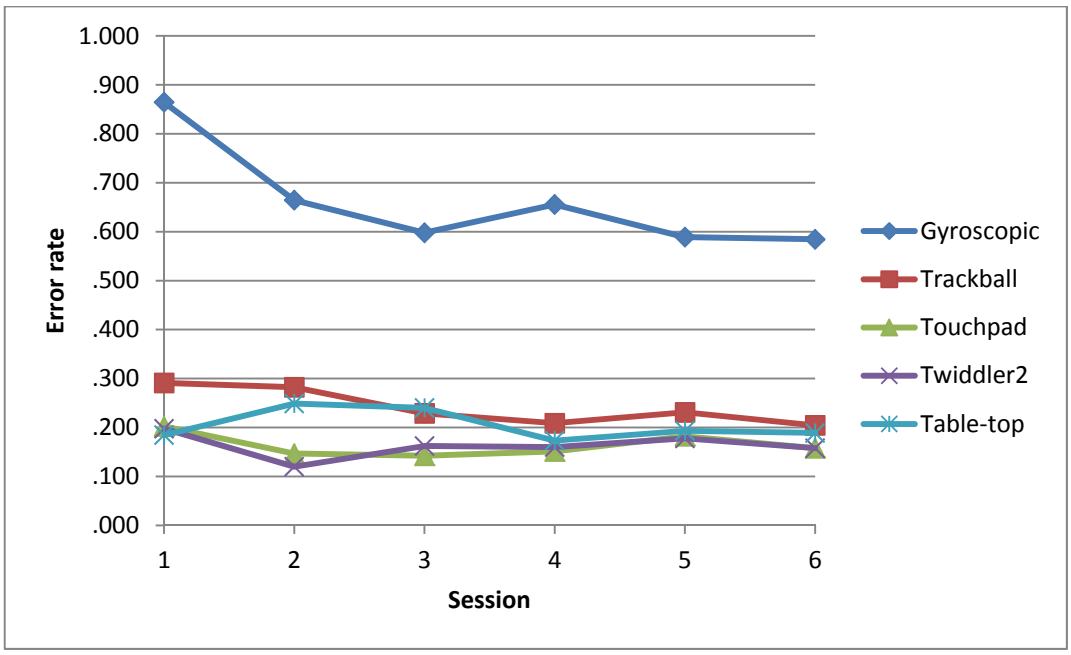


Figure 42: Mean error rate for device for all sessions (learnability study)

Across all sessions and trial conditions, pairwise comparisons revealed a significant difference between all the devices except for the; Touchpad and trackball and Touchpad and Twiddler2. Table 31 lists the mean error rate per device across all sessions. Across all sessions and devices, pairwise comparisons revealed a significant difference between all trial conditions (size and distance combinations) except for wheel combinations of 16 pixels x 300 pixels and 16 pixels x 500 pixels; 32 pixels x 300 pixels and 32 pixels x 500 pixels; 32 pixels x 300 pixels and 48 pixels x 500 pixels; 48 pixels x 300 pixels and 48 pixels x 500 pixels. Table 32 lists the mean error rate per wheel (size and distance) combinations across all sessions.

Table 31: Error rate per device across all sessions (learnability study)

Device	Mean	Std. dev.
Twiddler2	0.16	0.23
Touchpad	0.16	0.24
Table-top mouse	0.20	0.26
Trackball	0.24	0.31
Gyroscopic	0.66	0.69

Table 32: Error rate per wheel (size x distance) combination across all sessions. Target sizes are 16, 32 and 48 pixels and distances are 300 and 500 pixels, i.e. wheel 16 x 500 represents a target size of 16 pixels placed at 500 pixels apart. (learnability study)

Wheel	Mean	Std. dev.
48 x 300	0.16	0.23
48 x 500	0.18	0.25
32 x 300	0.23	0.33
32 x 500	0.27	0.37
16 x 300	0.49	0.60
16 x 500	0.51	0.66

Session Five and Session Six Analysis (Error Rate)

Across all devices (excluding the table-top mouse) and wheel (size and distance) combinations the mean trial error rate (one trial) for session five was 0.30 (SD 0.42).

A 4 (device) x 6 (wheel) ANOVA was conducted on the measure of error rate (one trial) for session five. Analysis revealed that there was significant effect of device $F_{(1.445,20.226)}$ = 21.665, $p < 0.05$, and wheel $F_{(2.014,28.190)}$ = 18.098, $p < 0.05$ on movement time. There was a significant interaction between device and wheel $F_{(4.328,60.586)}$ = 6.077, $p < 0.05$ (depicted in Figure 43). Pairwise comparisons of device reveal that the gyroscopic mouse is significantly different from all other devices. Across all devices, pairwise comparisons revealed a significant difference between all wheel conditions (i.e. size and distance combinations) except for:

- 16 x 300 pixels and 16 x 500 pixels;
- 32 x 300 pixels and 32 x 500 pixels;
- 32 x 300 pixels and 48 x 300 pixels;
- 32 x 300 pixels and 48 x 500 pixels;
- 32 x 500 pixels and 48 x 300 pixels;
- 32 x 500 pixels and 48 x 500 pixels; and
- 48 x 300 pixels and 48 x 500 pixels.

Across all devices (excluding the table-top mouse) and wheels (size x distance combinations) the mean trial error rate (one trial) for session six was 0.28 (SD 0.44).

A 4 (device) x 6 (wheel) ANOVA was conducted on the measure of error rate (one trial) for session six. The analysis revealed that there was significant effect of device $F_{(1.35,18.92)}$ = 11.62, $p < 0.05$, and wheel $F_{(1.80,25.08)}$ = 10.55, $p < 0.05$ on movement time. There was a

significant interaction between device and wheel $F_{(4.76,66.63)} = 2.68$, $p < 0.05$ (illustrated in Figure 43). Pairwise comparisons of device reveal that the gyroscopic mouse is significantly different from all other devices. Across all devices, pairwise comparisons reveal that the wheel combination of 16 pixels x 300 pixels is significantly different from all other size and distance combinations. Table 33 lists the mean error rate for device and wheel (size and distance) combinations for sessions five and six.

Table 33: Session five and session six mean device and wheel error rate. Target sizes are 16, 32 and 48 pixels and distances are 300 and 500 pixels, i.e. wheel 16 x 500 represents a target size of 16 pixels placed at 500 pixels apart. (learnability study)

	Mean error rate	
Device	**Session Five**	**Session Six**
Twiddler2	0.18 (0.22)	0.16 (0.28)
Touchpad	0.18 (0.26)	0.16 (0.22)
Table-top mouse	0.19 (0.24)	0.19 (0.24)
Trackball	0.23 (0.30)	0.20 (0.30)
Gyroscopic	0.59 (0.63)	0.58 (0.67)
Wheel	**Session Five**	**Session Six**
48 x 300	0.16 (0.19)	0.15 (0.20)
48 x 500	0.17 (0.27)	0.17 (0.26)
32 x 300	0.21 (0.24)	0.21 (0.33)
32 x 500	0.26 (0.33)	0.23 (0.35)
16 x 300	0.46 (0.29)	0.46 (0.61)
16 x 500	0.51 (0.59)	0.44 (0.63)

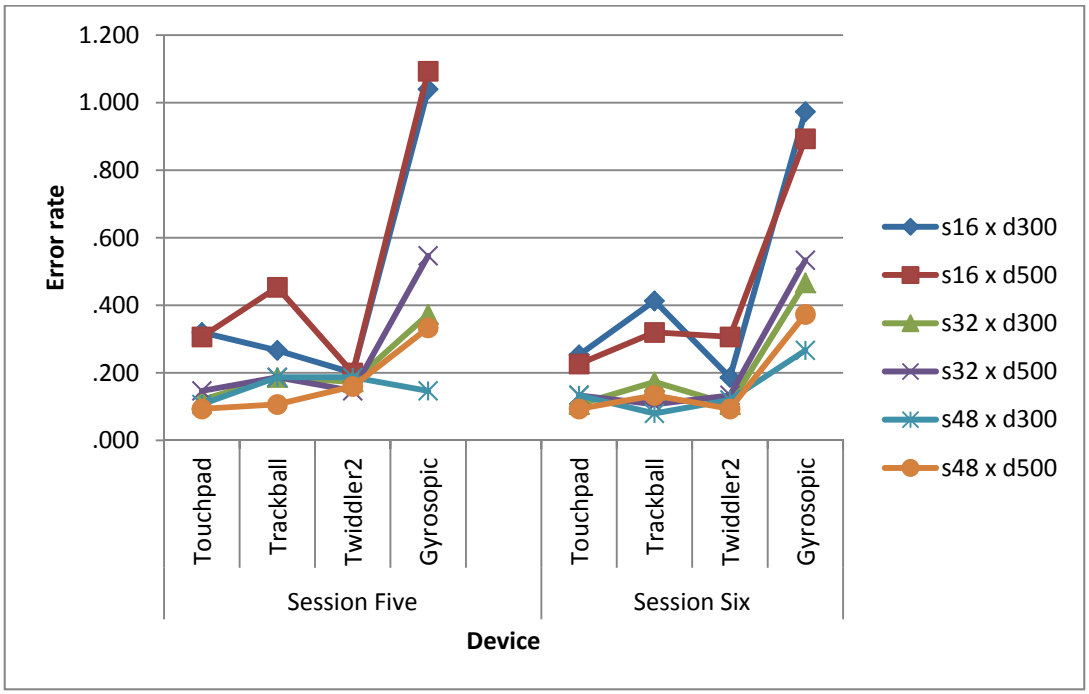


Figure 43: Device and wheel interaction for error rate - sessions five and six (learnability study)

Table 34: Difference between devices for each wheel (size and distance) combination – error rate. Target sizes are 16, 32 and 48 pixels and distances are 300 and 500 pixels, i.e. wheel 16 x 500 represents a target size of 16 pixels placed at 500 pixels apart. Std. dev. in parenthesis (learnability study)

Wheel	Device	Mean (Session Five)	Mean (Session Six)	Significant effect and post hoc comparisons
16 x 300	Twiddler2	0.20 (0.15)	0.19 (0.21)	Session 5: $F_{(1.390,19.464)} = 12.844$, $p < 0.05$ gyroscopic and Twiddler2; gyroscopic and trackball; gyroscopic and touchpad Session 6: $F_{(1.51,21.19)} = 7.70$, $p < 0.05$ gyroscopic and Twiddler2
	Trackball	0.27 (0.32)	0.41 (0.42)	
	Touchpad	0.32 (0.35)	0.25 (0.30)	
	Gyroscopic	1.04 (0.84)	0.97 (0.92)	
16 x 500	Twiddler2	0.20 (0.28)	0.31 (0.57)	Session 5: $F_{(1.968,27.553)} = 14.210$, $p < 0.05$ gyroscopic and Twiddler2; gyroscopic and trackball; gyroscopic and touchpad; trackball and Twiddler2 Session 6: $F_{(1.49,20.89)} = 7.04$, $p < 0.05$ gyroscopic and touchpad
	Touchpad	0.31 (0.34)	0.23 (0.29)	
	Trackball	0.45 (0.47)	0.32 (0.38)	
	Gyroscopic	1.09 (0.72)	0.89 (0.91)	
32 x 300	Touchpad	0.12 (0.13)	0.11 (0.10)	Session 5: $F_{(3,42)} = 5.611$, $p < 0.05$ gyroscopic and touchpad Session 6: $F_{(1.63,22.82)} = 6.30$, $p < 0.05$ gyroscopic and Twiddler2
	Twiddler2	0.17 (0.23)	0.11 (0.18)	
	Trackball	0.19 (0.18)	0.17 (0.23)	
	Gyroscopic	0.37 (0.33)	0.47 (0.53)	
32 x 500	Touchpad	0.15 (0.16)	0.13 (0.16)	Session 5: $F_{(1.647,23.060)} = 9.856$, $p < 0.05$ gyroscopic and Twiddler2; gyroscopic and touchpad Session 6: $F_{(1.43,20.06)} = 7.75$, $p < 0.05$ gyroscopic and trackball
	Twiddler2	0.15 (0.21)	0.13 (0.16)	
	Trackball	0.19 (0.24)	0.11 (0.15)	
	Gyroscopic	0.55 (0.46)	0.53 (0.54)	
48 x 300	Touchpad	0.11 (0.18)	0.13 (0.18)	Session 5: No significant effect. Session 6: $F_{(3,42)} = 3.46$, $p < 0.05$ gyroscopic and trackball
	Gyroscopic	0.15 (0.14)	0.27 (0.24)	
	Twiddler2	0.19 (0.24)	0.12 (0.15)	
	Trackball	0.19 (0.18)	0.08 (0.18)	
48 x 500	Touchpad	0.09 (0.21)	0.09 (0.23)	Session 5: $F_{(1.908,26.707)} = 3.610$, $p < 0.05$ No pair-wise significance Session 6: $F_{(1.75,24.45)} = 5.70$, $p < 0.05$ No pair-wise significance
	Trackball	0.11 (0.17)	0.13 (0.18)	
	Twiddler2	0.16 (0.23)	0.09 (0.17)	
	Gyroscopic	0.33 (0.37)	0.37 (0.34)	

6.4.5.1 Differences Between Devices for Wheel Combinations (Error)

Each wheel (target size and distance) combination was analysed separately in order to determine whether there was a significant difference between the devices for sessions five and six. For each wheel combination in sessions five and six, there was a significant effect of device on error rate; pairwise comparisons revealed a significant difference between the devices. Table 34 outlines the difference between the devices for each wheel combination.

6.4.6 Fitts' Law Testing of Pointing Devices

Across all devices (excluding the table-top mouse) and sessions, the mean throughput was 2.37 bps (SD 0.37). A 4 (device) x 6 (session) ANOVA was conducted on the measure of throughput. The analysis revealed that there was significant effect of device $F_{(3,42)}$ = 16.843, $p < 0.05$ and session on $F_{(5,70)}$ = 46.481, $p < 0.05$ on throughput. There was a significant interaction between device and session $F_{(15,210)}$ = 2.076, $p < 0.05$. Participants' performance improved with the devices over the course of the six sessions. Across all devices, Helmert contrasts reveal no significant differences from session 4 onwards. Figure 44 depicts the throughput (bps) for all devices for all sessions. Across all sessions, pairwise comparisons revealed a significant difference between the following devices; gyroscopic mouse and touchpad mouse, gyroscopic mouse and Twiddler2, touchpad and Twiddler2, trackball and Twiddler2. Table 35 lists the mean throughput for all devices across all sessions.

Table 35: Throughput (bps) per device across all sessions (learnability study)

Device	Throughput (bps)	Std. dev.
Twiddler2	2.13	0.33
Gyroscopic	2.33	0.34
Trackball	2.46	0.31
Touchpad	2.57	0.34
Table-top mouse	4.78	0.41

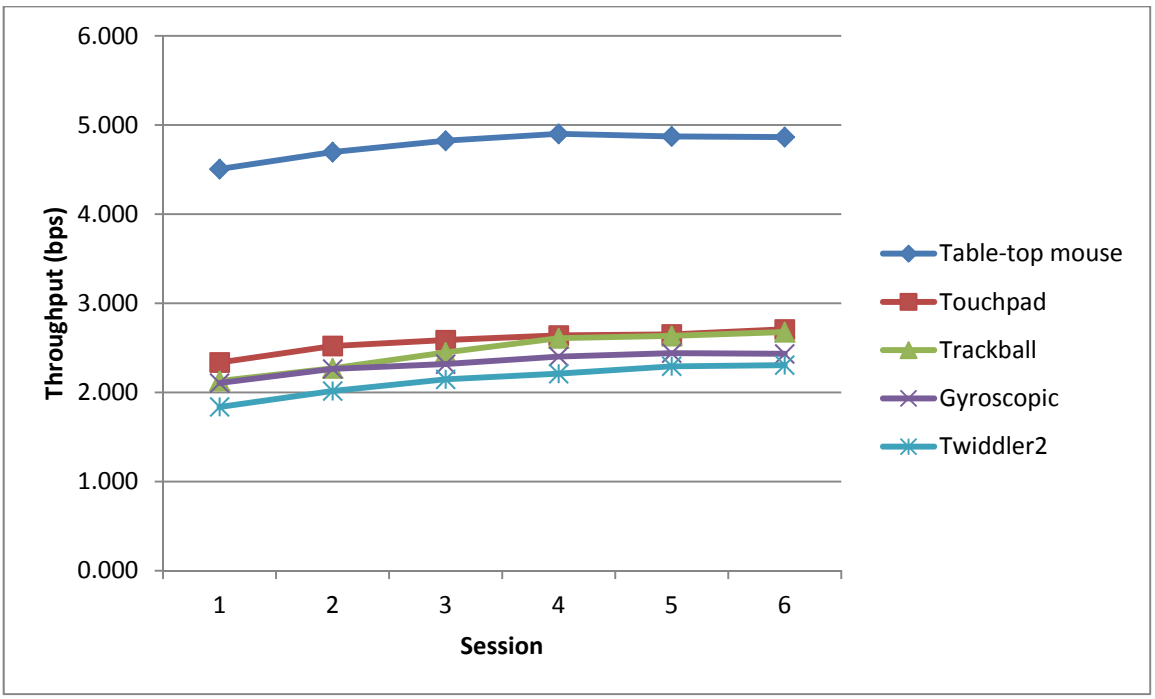


Figure 44: Throughput (bps) for all devices over all sessions (learnability study)

Throughput is evaluated once learning has stabilised [13], therefore, the following analysis is performed on session 5 and session 6 data as is done in other studies [182]. Doing so will provide a measure of practiced performance.

6.4.6.1 Does it Fitts?

If devices follow Fitts' law, the dependent measure of throughput can be used as a means for comparison [13]. A least-squares linear regression is used in order to determine whether there is a linear relationship between movement time and index of difficulty, and therefore to determine whether Fitts' law applies [13].

In the Fitts' law equation seen below:

$$MT = a + b \times ID_e$$

the intercept (a) and the slope (b) parameters are found using a least-squares linear regression [13]. Linear regression is used to ascertain how well the regression line fits the observed data [13]. Figure 45 (session five) and Figure 46 (session six) illustrate the regression line for every device for sessions five and six respectively. Of interest to this study is that the devices follow Fitts' law as seen by the high R^2 values listed in Table 36 indicating that the model provides a good description of the observed behaviour. R^2 values are greater than 0.91 for session five and greater than 0.93 for session six. For

experiments involving measurements on human participants, correlations above 0.90 are considered very high [175]. The high R^2 values indicate that over 91% of movement time is determined by index of difficulty for session five and 93% for session six. In light of this, Fitts' law applies to the use of the devices while performing pointing and selection tasks in a wearable context.

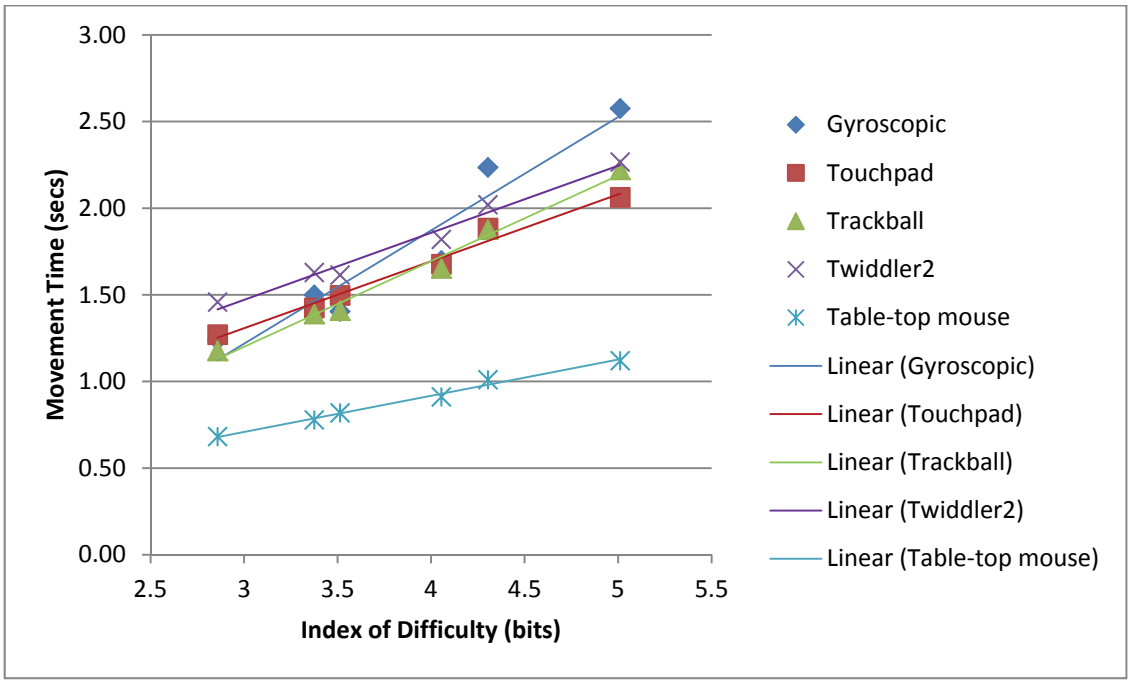


Figure 45: Movement time (seconds) for index of difficulty (bits) for each device - session five (learnability study)

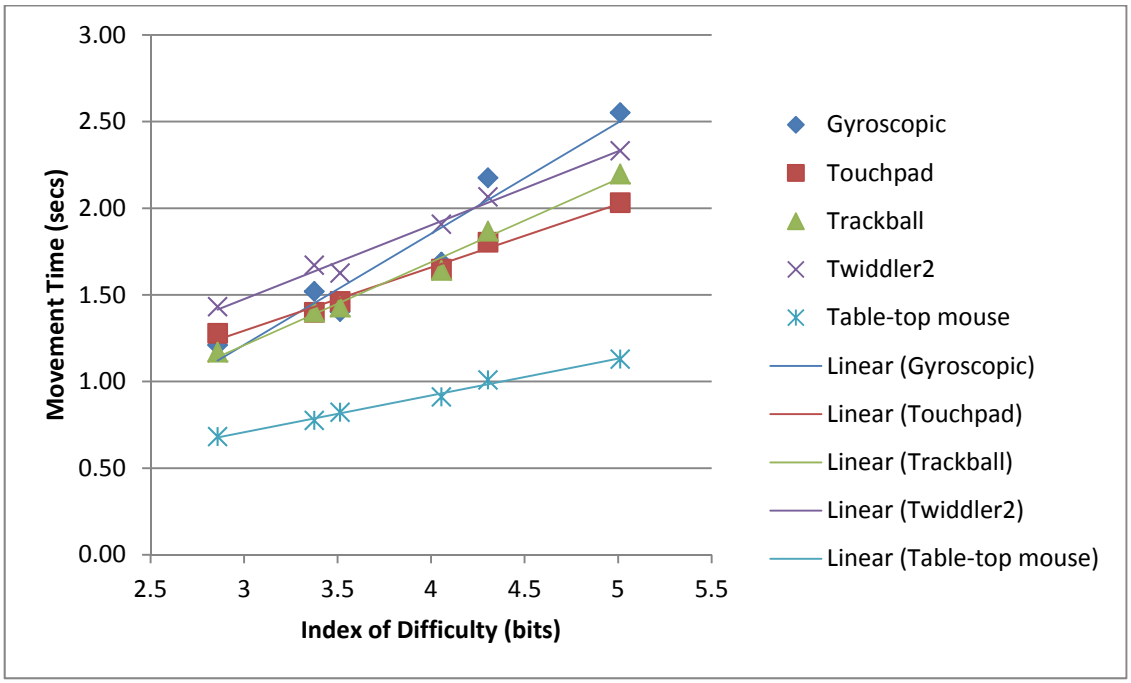


Figure 46: Movement time (seconds) for index of difficulty (bits) for each device - session six (learnability study)

Table 36: Fitts' law models for devices - sessions five and six (learnability study)

Session Five			
Device	**Intercept (a)**	**Slope (b)**	R^2
Gyroscopic	-0.74	0.65	0.9192
Twiddler2	0.31	0.39	0.9759
Touchpad	0.15	0.39	0.9805
Trackball	-0.28	0.49	0.9852
Table-top mouse	0.08	0.21	0.9897
Session Six			
Device	**Intercept (a)**	**Slope (b)**	R^2
Gyroscopic	-0.7113	0.641	0.9301
Twiddler2	0.1962	0.4264	0.9857
Trackball	-0.2318	0.4802	0.9872
Touchpad	0.1997	0.3647	0.988
Table-top mouse	0.0706	0.2122	0.9907

6.4.6.2 Throughput (bps) (Session Five and Session Six)

Across all devices, the mean throughput (excluding table-top mouse) for session five is 2.50 bps (SD 0.37). There was a significant effect of device on throughput $F_{(3,42)}$ = 6.34, $p < 0.05$. Pairwise comparisons revealed a significant difference between the following device pairs; touchpad and Twiddler2 and trackball and Twiddler2. Table 37 lists the throughput (bps) values for the devices for sessions five and six.

For session six, the mean throughput for all devices (excluding the table-top mouse) is 2.53 bps (SD 0.34). Device has a significant effect on throughput $F_{(3,42)}$ = 11.976, $p <$ 0.05. Post hoc comparisons revealed a significant difference between the following pairs; gyroscopic and touchpad, gyroscopic and trackball, touchpad and Twiddler2 and trackball and Twiddler2.

Table 37: Throughput (bps) for session five, six and across both (learnability study). Standard deviation in parenthesis

Device	Session Five	Session Six	Mean
Twiddler2	2.29 (0.32)	2.31 (0.34)	2.30 (0.32)
Gyroscopic	2.44 (0.43)	2.43 (0.29)	2.44 (0.37)
Trackball	2.63 (0.28)	2.68 (0.20)	2.66 (0.24)
Touchpad	2.65 (0.36)	2.71 (0.35)	2.68 (0.35)
Table-top mouse	4.87 (0.41)	4.86 (0.39)	4.87 (0.39)

6.4.6.3 Movement Time (Session Five and Session Six)

Mean movement time across all devices (excluding the table-top mouse) for session five is 1.71 seconds (SD 0.26). There was a significant effect of device on movement time for session five $F_{(3,42)}$ = 3.59, $p < 0.05$, however pair-wise comparisons reveal no significant differences.

Mean movement time across all devices (excluding table-top mouse) for session six is 1.71 seconds (SD 0.25). A significant effect of device on movement time $F_{(1.98,27.74)}$ = 7.18, $p < 0.05$ was found for session six. Post hoc comparisons reveal a significant difference between the gyroscopic and touchpad, trackball and Twiddler2 devices. Table 38 lists the mean movement time (seconds) for all devices for sessions five and six.

Table 38: Mean movement time (seconds) for session five and six (learnability study). Standard deviation in parenthesis

Device	Session Five	Session Six
Table-top mouse	0.89 (0.07)	0.89 (0.07)
Trackball	1.62 (0.17)	1.62 (0.15)
Touchpad	1.64 (0.23)	1.60 (0.23)
Gyroscopic	1.78 (0.32)	1.76 (0.26)
Twiddler2	1.80 (0.27)	1.84 (0.28)

Table 39: Accuracy (% error) for session five and six (learnability study). Standard deviation in parenthesis

Device	Session five	Session six
Touchpad	0.02 (0.02)	0.02 (0.02)
Twiddler2	0.03 (0.02)	0.02 (0.03)
Trackball	0.03 (0.03)	0.03 (0.02)
Gyroscopic	0.08 (0.05)	0.08 (0.07)
Table-top mouse	0.03 (0.02)	0.03 (0.02)

Table 40: Button press time (milliseconds) and cursor movement distance (pixels) while performing click operation - session five and session six (learnability study). Standard deviation in parenthesis

Session	Device	Mean	Significant effect	Post hoc comparisons
Button Press Time (millisecs)				
Session 5	Mouse	67.98 (11.81)	$F_{(3,42)} = 12.536, p < 0.05$	gyroscopic and touchpad; gyroscopic and trackball; touchpad and Twiddler2
	Touchpad	109.64 (12.73)		
	Trackball	119.12 (17.23)		
	Twiddler2	130.59 (20.27)		
	Gyroscopic	141.78 (23.52)		
Session 6	Mouse	68.52 (11.93)	$F_{(3,42)} = 18.251, p < 0.05$	gyroscopic and touchpad; gyroscopic and trackball; gyroscopic and Twiddler2; touchpad and Twiddler2
	Touchpad	107.93 (11.44)		
	Trackball	121.66 (14.43)		
	Twiddler2	127.43 (19.19)		
	Gyroscopic	142.23 (17.62)		
Movement when Button Down (pixels)				
Session 5	Mouse	1.07 (0.75)	$F_{(3,42)} = 5.683, p < 0.05$	gyroscopic and touchpad
	Touchpad	0.17 (0.52)		
	Trackball	0.51 (0.65)		
	Twiddler2	0.39 (0.51)		
	Gyroscopic	1.00 (0.76)		
Session 6	Mouse	0.79 (0.43)	$F_{(1.77,24.81)} = 6.433, p < 0.05$	gyroscopic and touchpad
	Touchpad	0.07 (0.10)		
	Trackball	0.39 (0.70)		
	Twiddler2	0.37 (0.59)		
	Gyroscopic	1.21 (1.31)		

6.4.6.4 Accuracy (% Error) (Session Five and Session Six)

Mean percentage error rate across all devices (excluding table-top mouse) is 0.04 (SD 0.04) and 0.04 (SD 0.05) for sessions five and six respectively. Accuracy is significantly effected by device in session five $F_{(1.439,20.145)} = 24.569$, $p < 0.05$ and session six $F_{(1.338,18.738)} = 12.057$, $p < 0.05$. Post hoc comparisons revealed that the gyroscopic mouse is significantly different from all other devices for both sessions five and six. Table 39 lists the error rate for all devices in sessions five and six.

6.4.7 Button Press Information (Session Five and Session Six)

Button press information consists of the time taken to perform a click and the amount the cursor moves when the mouse button is pressed (i.e. performing a click operation). Mean button down/press time (excluding table-top mouse) for session five is 125.28

milliseconds (SD 22.04). Mean button down/press time (excluding table-top mouse) is 124.811 milliseconds (SD 19.884) for session six. Mean movement of cursor while button is pressed (excluding table-top mouse) for session five is 0.52 pixels (SD 0.68). Mean movement of cursor for session six is 0.51 pixels (SD 0.89). As seen in Table 40 , device has a significant effect on button press time and cursor movement distance when performing a click operation. Results of post hoc comparisons can also be seen in Table 40.

6.5 Workload and Survey Results

After sessions one, five and six, participants were asked to complete an exit questionnaire where they were asked to rate the devices on a seven point scale in terms of overall reaction and experience using the device. The first eleven questions were concerned with general attributes such as smoothness, comfort, speed, accuracy and overall operation of device, while the next five questions were concerned with the amount of effort required to operate the devices, followed by the remaining five questions pertaining to neck, shoulder, arm, wrist and finger fatigue caused by the devices.

This section reports the results for session five, that is, the findings after the participants were exposed to the pointing devices over five days. The mean rating across all participants and attributes for each of the devices is as follows (scale of 1 very difficult to 7 very easy): gyroscopic mouse 4.56 (SD 1.92); Twiddler2 5.75 (SD 1.30); trackball 5.76 (SD 1.34); and touchpad 6.16 (SD 1.20).

Figure 47 graphs the mean rating values across all participants for each attribute for each device (session five). The graph shows a preference for the touchpad, followed by the Twiddler2 and trackball ranked second. The gyroscopic mouse was ranked least favourable by participants.

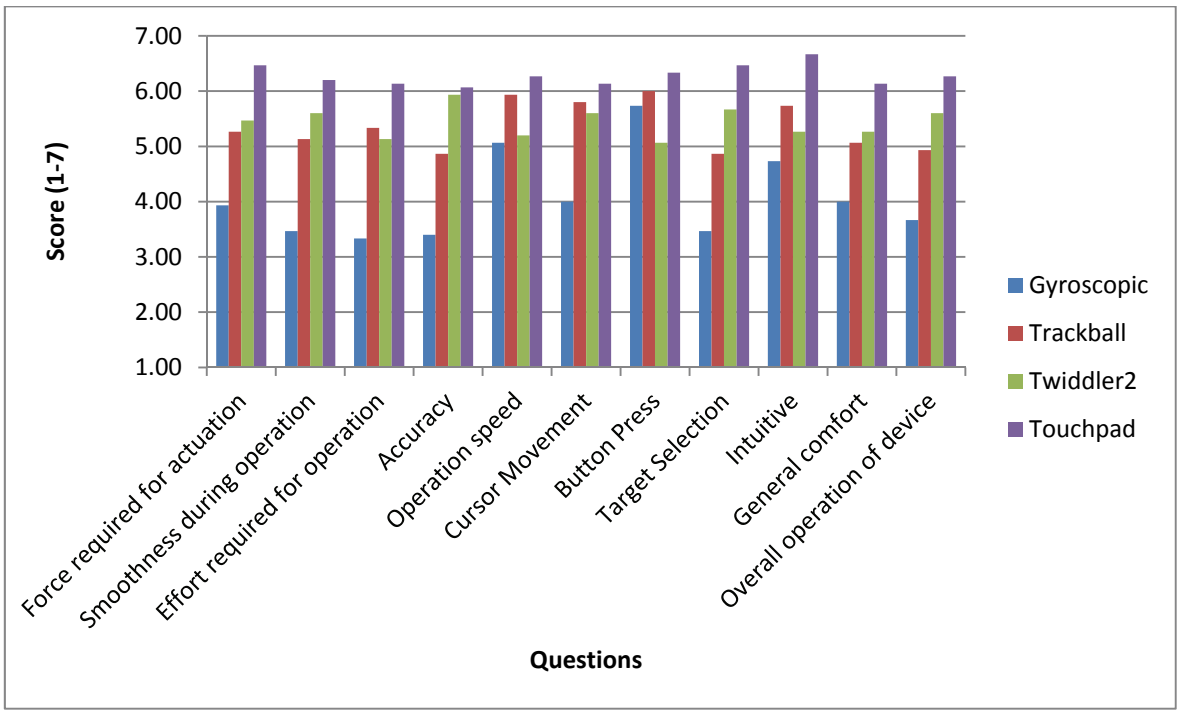


Figure 47: Mean values of general attributes - session five (learnability study)

Figure 48 and Figure 49 illustrate the amount of effort required and the level of fatigue experienced for all devices for session five.

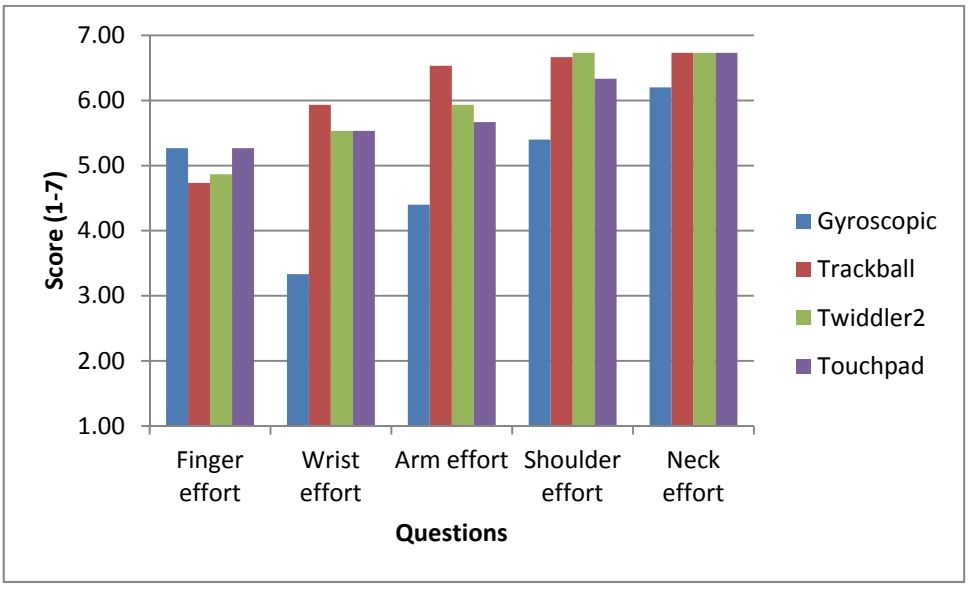


Figure 48: Mean values of effort required for devices - session five (learnability study)

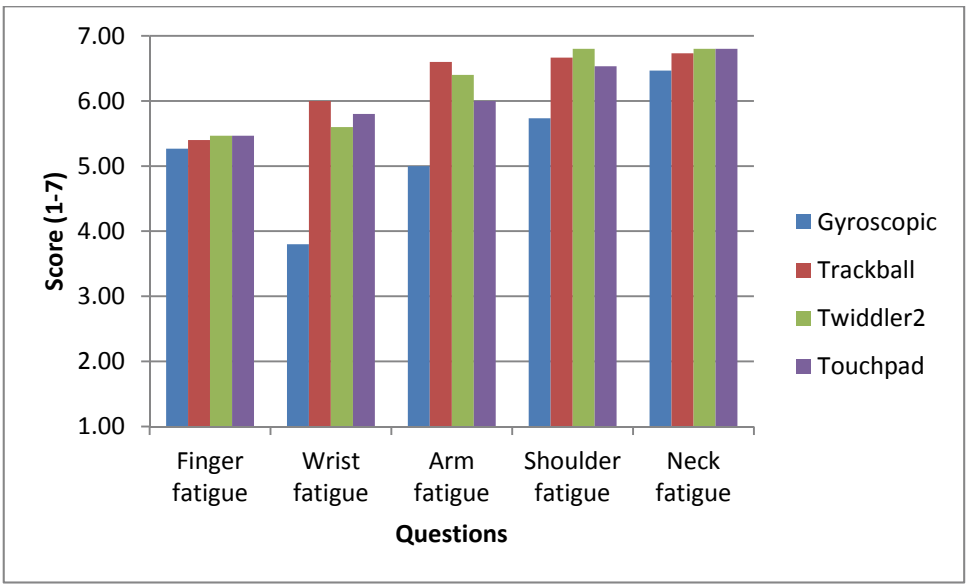


Figure 49: Mean values of fatigue caused by devices - session five (learnability study)

Participants were asked to explicitly rank the four pointing devices in order of 1st, 2nd, 3rd and 4th for ease of use and ease of learning. The frequency of responses is shown in Table 41. Ten participants ranked the touchpad as being easy to use, followed by eight ranking the Twiddler2 second, seven ranked the trackball third and thirteen ranked the gyroscopic mouse last. Ten people ranked the touchpad as being easy to learn, ten ranked the trackball as second, nine the Twiddler2 and twelve ranked the gyroscopic mouse last.

Table 41: Participant rankings (learnability study)

	Ease of use				***Ease of learning***			
Rank	**Touchpad**	**Twiddler2**	**Trackball**	**Gyroscopic**	**Touchpad**	**Twiddler2**	**Trackball**	**Gyroscopic**
1	10	3	2	0	10	3	2	0
2	3	8	4	0	4	1	10	0
3	2	4	7	2	0	9	3	3
4	0	0	2	13	1	2	0	12

Participants were asked which device they would prefer to use in a wearable context, eleven preferred the touchpad, two the Twiddler2 and two the trackball. Nine participants stated that they felt they performed more consistently with the touchpad over the five days, five identified the Twiddler2 as facilitating consistent performance and

one the trackball mouse. Seven participants indicated that they improved the most with the trackball mouse, five the Twiddler2 and three the gyroscopic mouse.

Five participants used the A key to perform selection operations when using the Twiddler2 while ten participants used the E key. While using the touchpad mouse, all participants performed selection operations using a single tap rather than performing a left click using the thumb.

6.5.1 Workload

The mean overall workload across all devices (excluding the table-top mouse) and sessions was 31.28 (SD 26.16). A 4 (device) x 6 (session) ANOVA was conducted on the measure of overall workload. The analysis revealed that there was significant effect of device $F_{(3,42)}$ = 17.114, $p < 0.05$ and session on $F_{(2.65,37.11)}$ = 19.013, $p < 0.05$ on overall workload. There was no significant interaction between device and session. Post hoc testing revealed that the gyroscopic mouse is significantly different from the trackball, Twiddler2 and touchpad. The trackball is significantly different from the touchpad. The strength of the NASA-TLX scale is that it can be broken down and each subscale can be analysed individually in order to identify the source(s) of the workload problem [10, 17, 188, 191, 207, 251-253]. The following discussion evaluates each of the six sub-scales in turn.

Table 42 lists the mean overall workload for each device across all sessions. Helmert contrasts on session reveal that there is a significant difference for all except session 4 vs later. Session 5 vs Session 6 is significantly different. Figure 50 depicts the workload over all sessions for each device.

Mean overall workload (excluding the table-top mouse) for session five and six is 28.25 (SD 26.12) and 25.17 (SD 24.80) respectively. Session five analysis revealed that device significantly effects workload $F_{(2.10,29.34)}$ = 18.90, $p < 0.05$. The gyroscopic mouse is significantly different from the trackball, Twiddler2 and touchpad. Session six analysis revealed that device significantly effects workload $F_{(1.96,27.37)}$ = 11.06, $p < 0.05$. The gyroscopic mouse is significantly different from the trackball, Twiddler2 and touchpad. The trackball is significantly different from the touchpad.

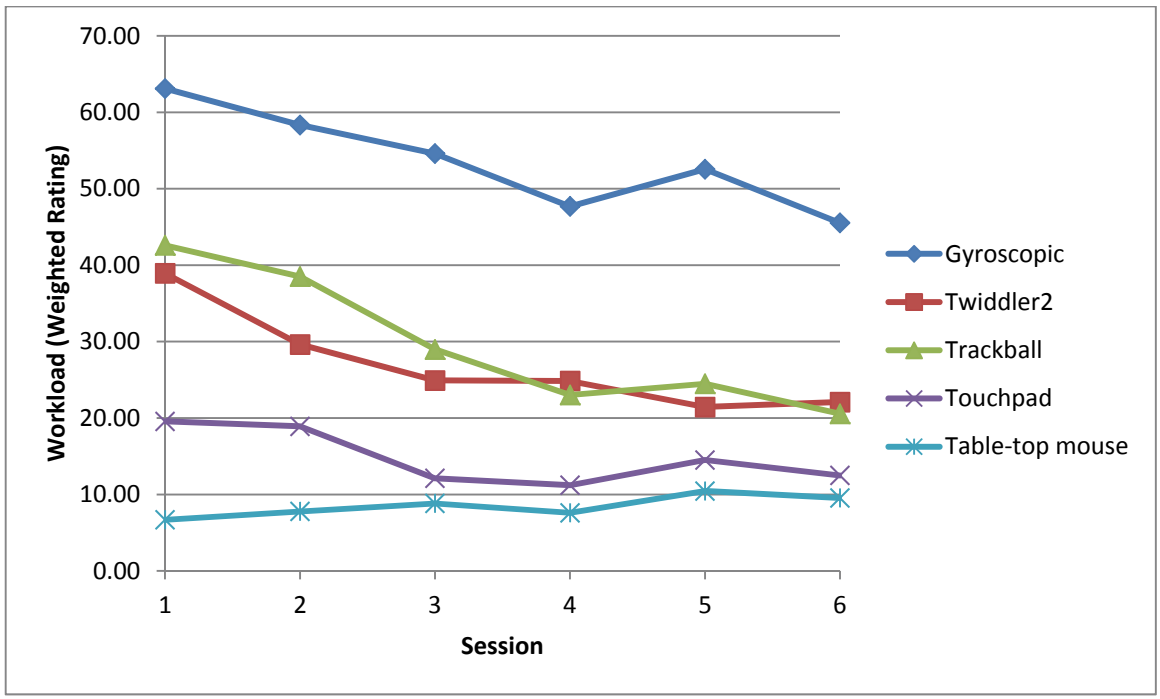


Figure 50: Workload over all sessions for each device (learnability study)

The strength of the NASA-TLX scale is that it can be broken down and each subscale can be analysed individually in order to identify the source(s) of the workload problem [10, 17, 188, 191, 207, 251-253]. The following discussion evaluates each of the six sub-scales in turn.

Table 42: Mean overall workload across all sessions for each device (learnability study)

Device	Mean	Std. dev.
Table-top mouse	8.48	9.48
Touchpad	14.80	13.09
Twiddler2	26.97	23.86
Trackball	29.69	23.34
Gyroscopic	53.64	25.97

6.5.1.1 Mental Demand

The mental demand workload across all devices (excluding the table-top mouse) and sessions was 27.60 (SD 27.07). A 4 (device) x 6 (session) ANOVA was conducted on the measure of mental demand. The analysis revealed that there was significant effect of device $F_{(1.83,25.67)} = 16.95$, $p < 0.05$ and session on $F_{(2.12,29.71)} = 12.94$, $p < 0.05$ on mental demand. There was a significant interaction between device and session $F_{(15,210)} = 1.86$, $p < 0.05$. Post hoc testing revealed that all devices are significantly different except for the trackball and Twiddler2. Helmert contrasts on session reveal that there is a significant difference for all except session 4 vs later. Session 5 vs Session 6 are significantly different. Figure 51 illustrates the mental demand for each device for all sessions.

The mental demand workload across all devices (excluding the table-top mouse) for session five was 24.92 (SD 26.61) and session six 21.58 (SD 25.64). Session 5 analysis revealed a significant difference between the gyroscopic mouse and touchpad $F_{(3,42)} = 9.20$, $p < 0.05$. Session 6 analysis revealed a significant difference between the trackball and touchpad and the gyroscopic mouse and the touchpad $F_{(1.86,26.04)} = 8.02$, $p < 0.05$.

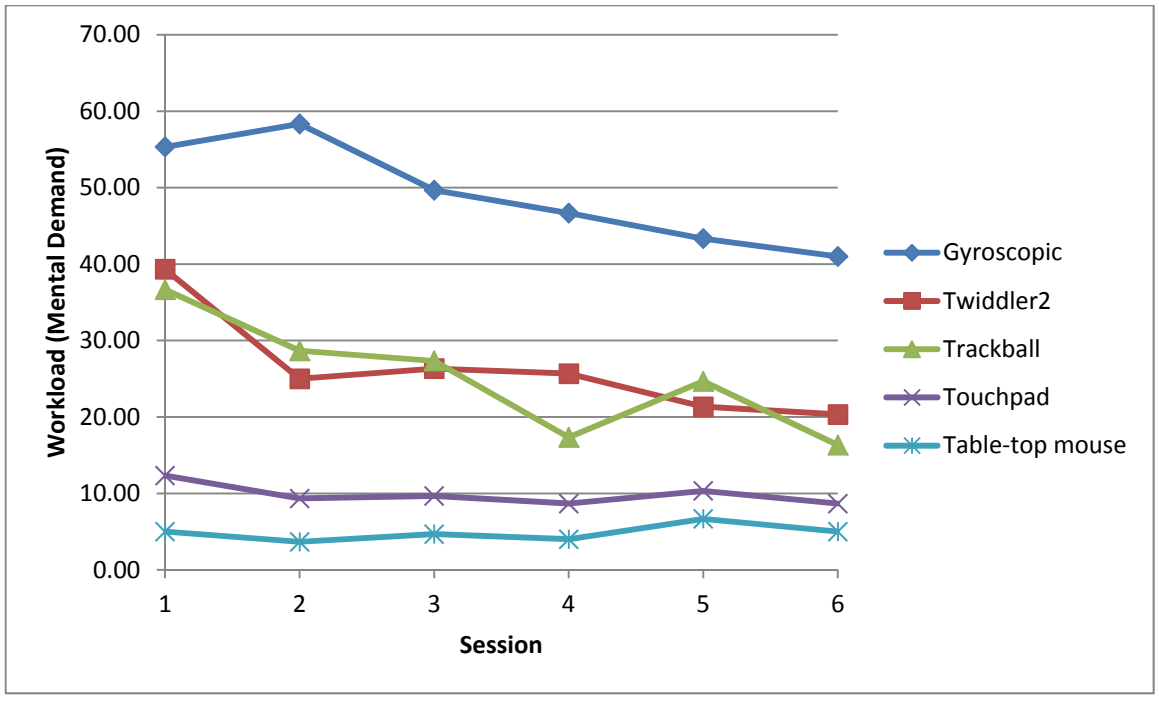


Figure 51: Mental demand over all sessions for each device (learnability study)

6.5.1.2 Physical Demand

The physical demand workload across all devices (excluding the table-top mouse) and sessions was 29.07 (SD 27.11). A 4 (device) x 6 (session) ANOVA on the measure of Physical Demand was conducted. The analysis revealed that there was significant effect of device $F_{(3,42)}$ = 11.43, $p < 0.05$ and session on $F_{(2.66,37.17)}$ = 9.59, $p < 0.05$ on physical demand. There was no significant interaction between device and session. Post hoc testing revealed that the gyroscopic mouse was significantly different from all other devices. Helmert contrasts on session reveal no significant difference from session 3 onwards. Figure 52 shows the physical demand for every device over all the sessions.

The physical demand workload across all devices (excluding the table-top mouse) for session five was 26.58 (SD 25.95) and session six 23.92 (SD 25.09). Session 5 analysis revealed a significant difference between the gyroscopic mouse and all other devices $F_{(1.83,25.8)}$ = 9.64, $p < 0.05$. Session 6 analysis revealed a significant difference between the following devices: gyroscopic and Twiddler2; gyroscopic and touchpad $F_{(3,42)}$ = 6.80, $p < 0.05$.

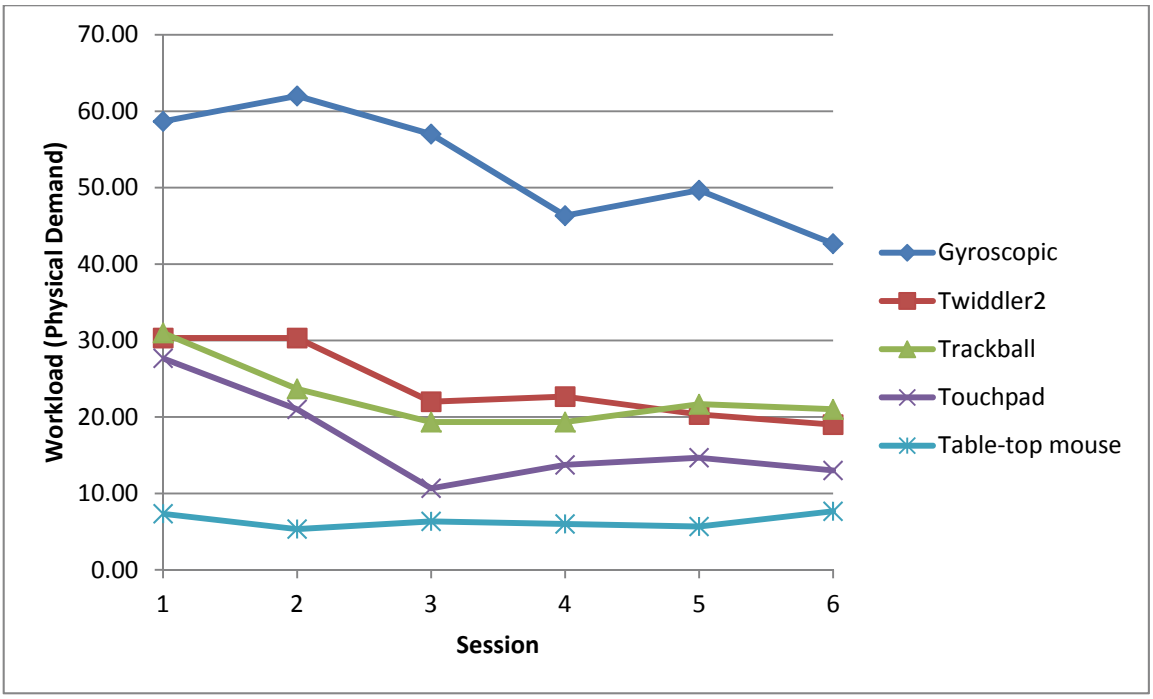


Figure 52: Physical demand over all sessions for each device (learnability study)

6.5.1.3 Temporal Demand

The temporal demand workload across all devices (excluding the table-top mouse) and sessions was 29.39 (SD 26.43). A 4 (device) x 6 (session) ANOVA was conducted on the measure of temporal demand. The analysis revealed that there was significant effect of device $F_{(3,42)}$ = 12.02, $p < 0.05$ and session on $F_{(1.84,25.79)}$ = 3.63, $p < 0.05$ on temporal demand. There was no significant interaction between device and session. Post hoc testing revealed significant differences between the following devices: trackball and touchpad; gyroscopic and Twiddler2; gyroscopic and touchpad. Helmert contrasts on session reveal no significant difference from session 2 onwards. Temporal demand for all devices over all sessions is depicted in Figure 53.

The temporal demand workload across all devices (excluding the table-top mouse) for session five was 29.17 (SD 28.02) and session six 26.75 (SD 29.54). Session 5 analysis revealed a significant difference between the gyroscopic mouse and touchpad $F_{(3,42)}$ = 8.35, $p < 0.05$. Session 6 analysis revealed a significant difference between gyroscopic and touchpad $F_{(3,42)}$ = 6.01, $p < 0.05$.

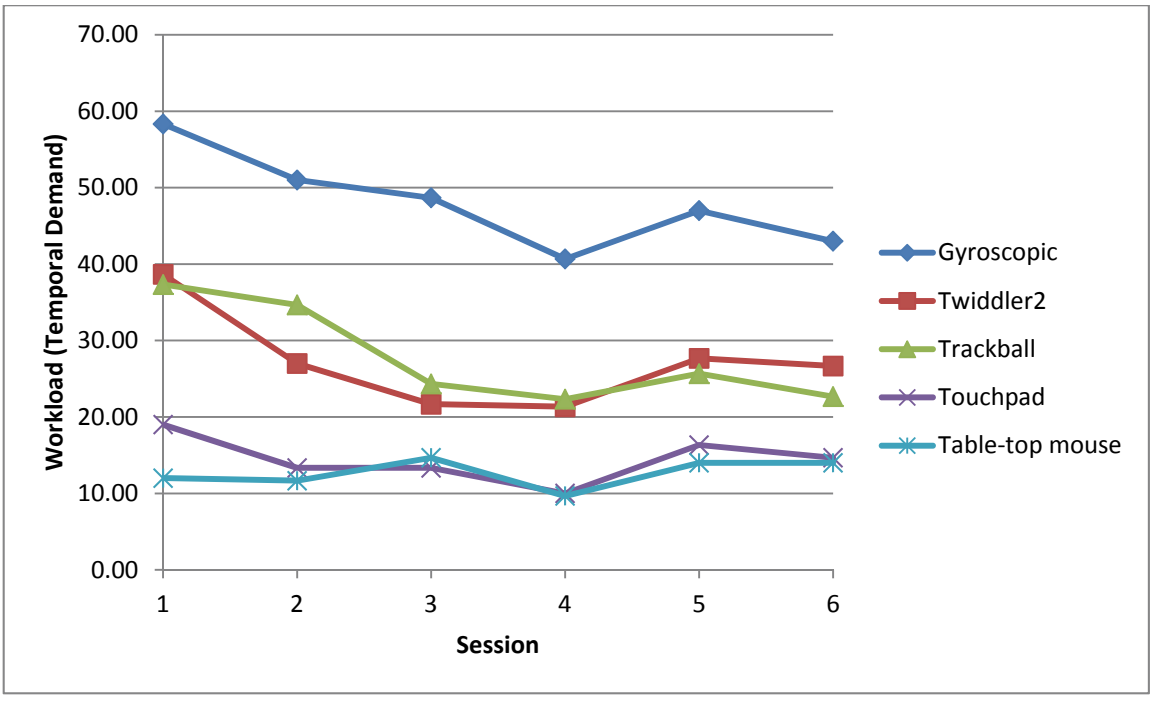


Figure 53: Temporal demand over all sessions for each device (learnability study)

6.3.1.4 Performance

Performance workload across all devices (excluding the table-top mouse) and sessions was 26.64 (SD 24.00). A 4 (device) x 6 (session) ANOVA on the measure of performance was conducted. The analysis revealed that there was significant effect of device $F_{(3,42)}$ = 14.07, $p < 0.05$ and session on $F_{(2.94,41.19)}$ = 8.41, $p < 0.05$ on performance. There was no significant interaction between device and session. Post hoc testing revealed significant differences between the gyroscopic mouse and all other devices. Helmert contrasts performed on session reveal that there is no significant difference from session 3 onwards. Performance for all sessions and devices is shown in Figure 54.

Performance across all devices (excluding the table-top mouse) for session five was 22.83 (SD 23.33) and session six 21.75 (SD 22.51). Session 5 analysis revealed a significant difference between the gyroscopic mouse and all other devices $F_{(3,42)}$ = 9.22, $p < 0.05$. Session 6 analysis revealed a significant difference between the gyroscopic and all other devices $F_{(1.89,26.33)}$ = 8.19, $p < 0.05$.

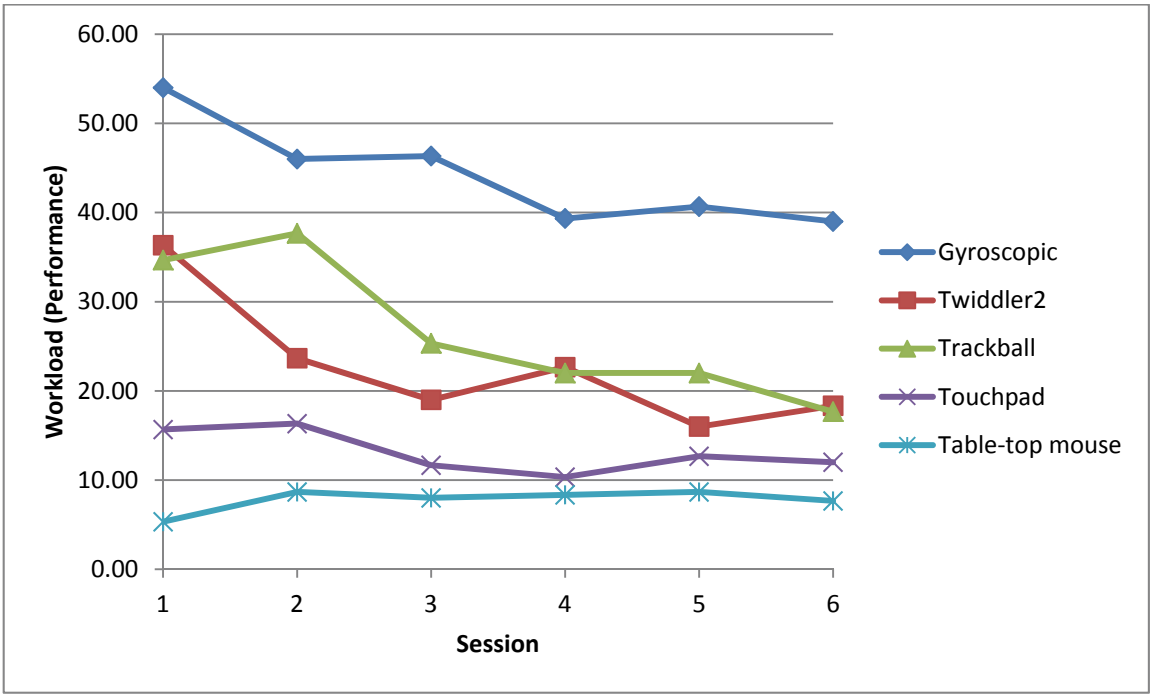


Figure 54: Performance over all sessions for each device (learnability study)

6.3.1.5 Effort

Effort workload across all devices (excluding the table-top mouse) and sessions was 31.54 (SD 28.45). A 4 (device) x 6 (session) ANOVA was conducted on the measure of effort. Analysis revealed that there was significant effect of device $F_{(3.42)}$ = 17.68, $p < 0.05$ and session on $F_{(5,70)}$ = 16.72, $p < 0.05$ on effort. There was no significant interaction between device and session. Post hoc testing revealed significant differences between the gyroscopic mouse and all other devices, as well as the trackball and touchpad. Helmert contrasts performed on session reveal a significant difference for all comparisons except session 4 vs later. Session 5 vs Session 6 is significantly different. Effort is seen in Figure 55 for all devices over all the sessions.

Effort across all devices (excluding the table-top mouse) for session five was 27.75 (SD 28.05) and session six 23.75 (SD 26.32). Session 5 analysis revealed a significant difference between the gyroscopic mouse and all other devices $F_{(3,42)}$ = 16.05, $p < 0.05$. Session 6 analysis revealed a significant difference between the following devices: trackball and touchpad; gyroscopic and Twiddler2; gyroscopic and touchpad $F_{(3,42)}$ = 9.57, $p < 0.05$.

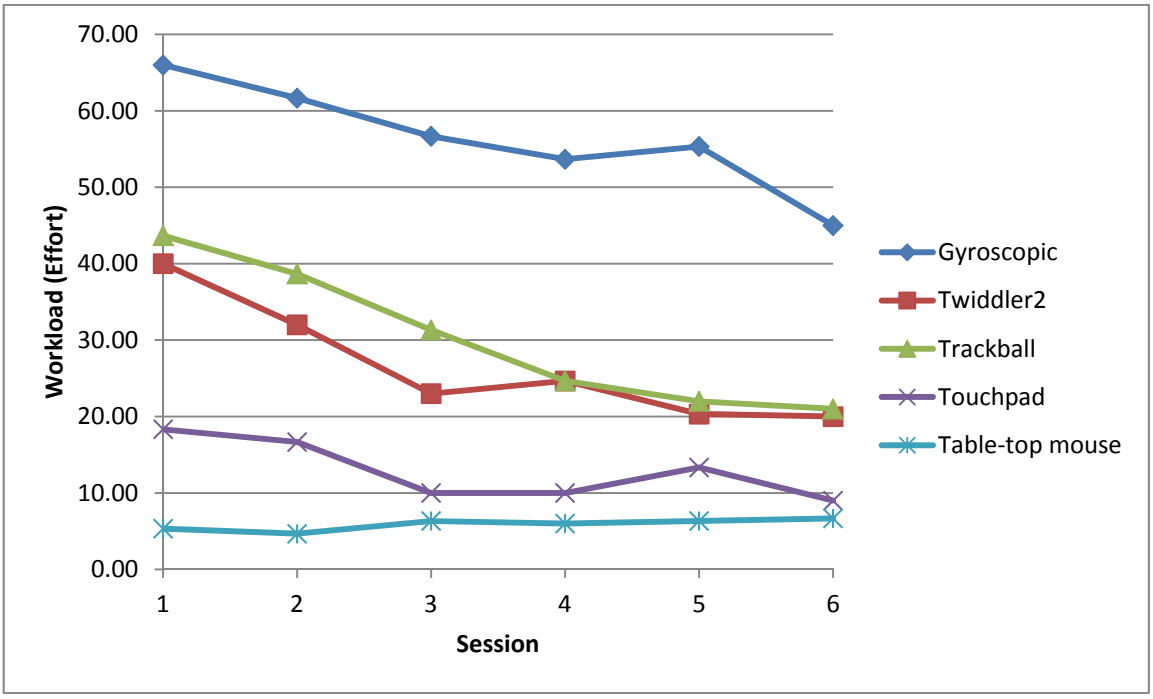


Figure 55: Effort over all sessions for each device (learnability study)

6.3.1.6 Frustration

Frustration workload across all devices (excluding the table-top mouse) and sessions was 31.71 (SD 29.25). A 4 (device) x 6 (session) ANOVA was conducted on the measure of frustration. Analysis revealed that there was significant effect of device $F_{(3.42)}$ = 15.81, $p < 0.05$ and session on $F_{(3.08,43.10)}$ = 13.10, $p < 0.05$ on frustration. There was no significant interaction between device and session. Post hoc testing revealed significant differences between the gyroscopic mouse and all other devices. Helmert contrasts on session reveal that there is no significant difference from session 4 onwards. Frustration is shown in Figure 56 for all devices and sessions.

Frustration across all devices (excluding the table-top mouse) for session five was 27.58 (SD 28.97) and session six 25.00 (SD 26.01). Session 5 analysis revealed a significant difference between the gyroscopic mouse and all other devices $F_{(2.21,31.00)}$ = 16.39, $p < 0.05$. Session 6 analysis revealed a significant difference between the gyroscopic mouse and all other devices $F_{(3,42)}$ = 10.31, $p < 0.05$.

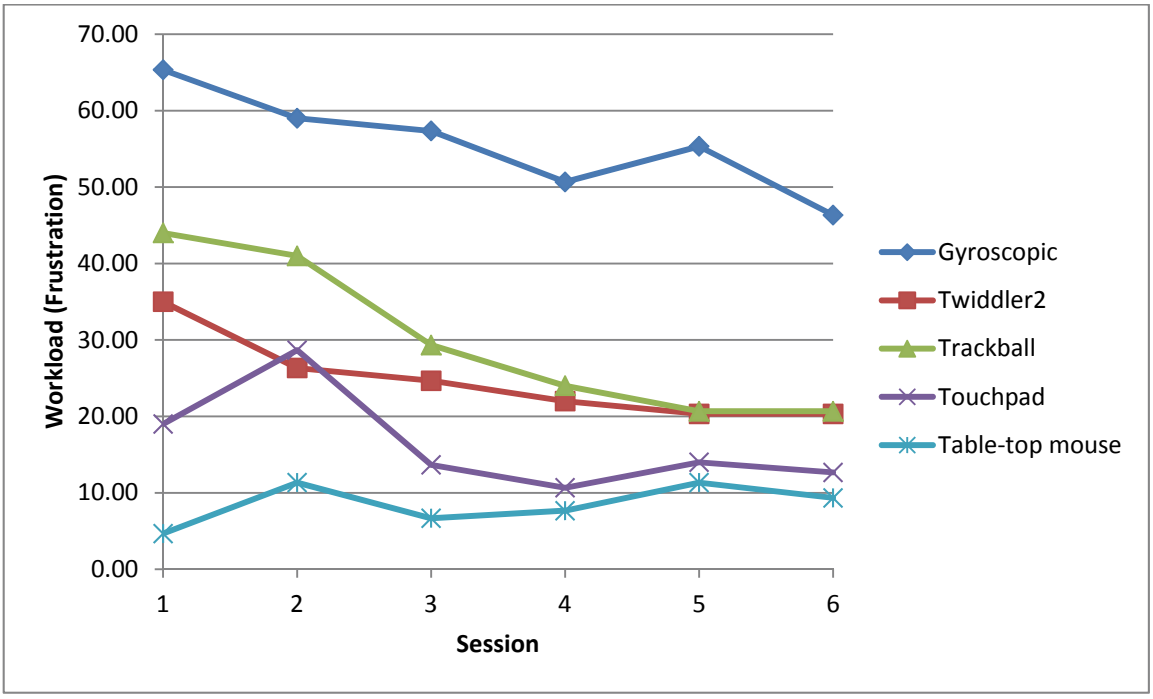


Figure 56: Frustration over all sessions for each device (learnability study)

6.6 Discussion

This section presents a discussion of the findings of the learnability extended study.

6.6.1 Learnability

Participants' performance improved with the devices given repeated exposure over the course of the five sessions as depicted in Figure 36 (supporting hypothesis 1). The rate of improvement differed depending upon the device. Regression equations for each device over the five sessions indicate that the Twiddler2, trackball and gyroscopic mouse show greater improvement with practice than the touchpad and table-top mouse. Participants demonstrated the largest rate of improvement of 22.01% from session 1 to session 5 when using the Twiddler2. The trackball improved by 19.18%, followed by the gyroscopic mouse at 14.26%. Participants improved the least by 12.56% while using the touchpad. Not surprisingly, given familiarity with the table-top mouse, participants demonstrated an improvement of 8.48%. Participants made fewer errors as the sessions progressed. Participants performed with 31.88% fewer errors from session 1 to session five when using the gyroscopic mouse. The trackball performed with 20.61% fewer errors, followed by the Twiddler2 with 10.11% and the touchpad with 9.89%.

The study confirms that there is a measurable difference between the devices in the time taken to see no more significant improvement over the six sessions (supporting hypothesis 2). Learning stabilised from session 3 onwards with the gyroscopic mouse. The touchpad and trackball performed comparably reaching asymptotic performance from session 4 onwards. Although showing the largest rate of improvement, the Twiddler2 showed no more significant improvement from session 5 onwards. In light of the longer learning curve, the Twiddler2 appears to take longer to learn than the other devices and is perhaps less intuitive in operation. Interestingly, the table-top mouse showed no significant improvement form session 3 onwards.

It may be inferred that learning has occurred if the performance achieved during practice (i.e. sessions 1 through 5) is retained in the retention test (i.e. session 6) [229, 230]. The performance achieved at the end of practice should be similar to the performance demonstrated in the retention test. A significant performance improvement between session 1 and session 6 is also evidence that learning has occurred [229]. All devices

demonstrated a significant improvement in performance between session one and session six. In addition, participants performed comparably between session 5 and session six, i.e. after the retention interval (supporting hypothesis 3), the improved device performance is permanent over time (persistence)). Interestingly, the Twiddler2 is the only of the four devices to perform with a slower mean task time in session 6 than in session 5 (although not significantly so) perhaps indicating that unless used frequently, is less memorable than that of other devices and the user may take longer to re-familiarise herself with the device.

6.6.2 Pointing Devices

Although session five analysis reports no significant difference between devices, it can be noted by observing session 4, 5 and 6 that there is a banding of the devices with the trackball and touchpad performing comparably faster than the gyroscopic mouse and Twiddler2. Analysis reveals a significant difference between the touchpad and Twiddler2 and the trackball and Twiddler2 in session 4 and 6, with session 6 also revealing a significant difference between the gyroscopic mouse and touchpad. Analysis of sessions 4, 5 and 6 reveals that the gyroscopic mouse performed with significantly more errors than the other devices.

6.6.3 Wheel Combinations

The study confirms that there is a measurable difference between the wheel (size and distance) combinations presented to participants (supporting hypothesis 4). Analysis of sessions 5 and 6 reveal that significant differences were found between all wheel combinations excluding the wheel condition of 32 pixels x 300 pixels and 48 pixels x 500 pixels. In light of this, the wheel (size and distance) combinations can be ordered as follows: participants performed fastest while selecting targets that were 48 pixels in size and positioned at 300 pixels apart. Participants performed comparably second fastest when selecting targets placed as follows; 48 pixels x 500 pixels and 32 pixels x 300 pixels. Targets positioned at 32 pixels x 500 pixels were third fastest. Participants performed the fourth and fifth slowest with target sizes of 16 pixels placed at 300 pixels and 500 pixels apart respectively. Analysis of sessions 5 reveals that the participants made significantly more errors with the smallest target size of 16 pixels over both distances (300 and 500

pixels). Analysis of session 6 reveals that the wheel combination of 16 pixels x 300 pixels performed with significantly more errors than the others.

6.6.4 Combined Results of Pointing Devices and Wheel Combinations

The trackball is seemingly the best choice of device for use with any of the target size and distance combinations for use in a wearable context. Similarly, target sizes of 48 pixels positioned at 300 pixels apart is the best choice for use with any of the pointing devices in a wearable context. The combination of the trackball and the target size/distance combination of 48 pixels x 300 pixels allows for the fastest selection time (supporting hypothesis 5). The gyroscopic mouse and touchpad are comparably the next fastest devices when selecting target sizes of 48 pixels positioned at 300 pixels apart. In the case where the target size of 48 pixels is not appropriate, the target size of 32 pixels could form a suitable choice performing with the next best time and performing comparably with the target size of 48 pixels and distance of 500 pixels. For target sizes of 32 pixels, positioned 300 pixels apart, the touchpad performed with the next best time after the trackball. The touchpad seemed to perform with fewer errors than the trackball pointing device. Interestingly and as found in the previous studies (Chapter 3 [226], Chapter 4 [134], and Chapter 5 [254]), the gyroscopic mouse tends to favour coarse mouse movements and performed comparably with the trackball when target sizes of 48 pixels were used (in either of the 300 pixel or 500 pixel distances). Performance of the gyroscopic mouse suffers with target sizes of 16 pixels (for both distance conditions). Precise movements with the wrist or arm necessary with target sizes of 16 pixels make the gyroscopic mouse a poor choice in this regard. In addition, typically the gyroscopic mouse performs with one of the highest error rates. Not surprisingly, the slowest target and distance combinations over all the devices in a wearable context are the target sizes of 16 pixels for both distances. The Twiddler2 performed with the slowest times over the 32 and 48 pixel target sizes (for both distances).

6.6.5 Fitts' Law

Importantly, Fitts' law applies to the evaluation of pointing devices in a wearable context (supporting hypothesis 8). Across sessions five and six, the mean throughput was as

follows: Twiddler2 2.30 bps, gyroscopic 2.44 bps, trackball 2.65 bps, touchpad 2.68 bps and mouse 4.87 bps. A 4 (device) x 2 (session) ANOVA found a significant effect of device on throughput $F_{(3,42)} = 9.42$, $p < 0.05$. Post hoc analysis revealed no significant difference found between the Twiddler2 and gyroscopic mouse and trackball and touchpad. In light of this, a ranking of the devices based on throughput can be established (supporting hypothesis 8). The trackball and touchpad performed comparably and have a significantly higher throughput than the Twiddler2 and gyroscopic mouse also performing comparably.

Across sessions five and six, the mean throughput for the mouse was 4.87 bps. The throughput value of 4.87 bps falls within the ranges of 3.7 – 4.9 bps as reported by Soukoreff and MacKenzie [13]. This finding suggests that a valid methodology was used given that the value of throughput derived for the desktop mouse is consistent with other studies [13] that calculate throughput in the same way. Soukoreff and MacKenzie [13] report throughput ranges of 0.99 – 2.9 bps for the touchpad and 1.6 – 2.55 bps for the isometric joystick. Although the values reported by Soukoreff and MacKenzie are not derived in a wearable context, the throughput values derived in this study for the touchpad (2.68 bps) and Twiddler2 (2.30 bps) are placed within these ranges.

As previously stated, very few studies have evaluated the dependent measure of throughput for input devices in a wearable context. Hwang et al. [140] derived a mean throughput value of 2.27 bps for the analogue joystick. However, the authors do not state how the measure of throughput is calculated and the display device used is also not described. The study undertaken by Calvo et al. [143] appears to be one of the few studies that uses Fitts' law in a wearable context following the recommendations made by Soukoreff and Mackenzie [13] which support and supplement the ISO 9241-9 standard. Calvo et al. [143] report that the touchpad performed with a throughput of 2.46 bps (SD 0.15) and is similar to that obtained in this study. The trackpoint however performed with a throughput of 1.49 bps (SD 0.07). Both of the input devices were embedded into an operational small wearable computer (MR-1 GD2000). Participants wore a small wearable computer on a tactical vest with the experimental conditions displayed on the small flip-down 5.6" screen. Hong et al. [217] report a throughput of 2.22 bps for a Dolphin mouse trackball evaluated in a wearable context while employing dynamic gain, whereas normal gain reports a throughput of 1.59 bps. The desktop condition with

standard mouse reports 5.88 bps improving by 0.66 bps when dynamic gain was employed. Throughput however is calculated using the reciprocal of the slope of the regression line ($1/b$) instead of mean of means. Calculating throughput using the slope of regression line tends to inflate the throughput value [14] and has been noted as being influenced by the range of ID values used [13]. The limitations of calculating throughput using the reciprocal of the slope of the regression line ($1/b$) is explained by Soukoreff and Mackenzie [13].

6.6.6 Workload and Survey

The study confirms that there is a measurable difference in workload when using the pointing devices in a wearable context (supporting hypothesis 6). Across all the sessions, the mean overall workload for the touchpad was 14.80, followed by the Twiddler2 26.97, trackball 29.69 and lastly the gyroscopic mouse 53.64. The gyroscopic mouse is significantly different from the trackball, Twiddler2 and touchpad. The trackball is significantly different from the touchpad. In light of this, a ranking based on overall workload can be established (supporting hypothesis 6) the touchpad has the lightest workload rating, this is followed by the Twiddler2 and the trackball performing comparably with the second lightest workload rating (there is no significant difference reported between the touchpad and twiddler2 and Twiddler2 and trackball) and lastly the workload was significantly heavier for the gyroscopic mouse (ranking last and reporting a significant difference from all of the other devices).

The study presented by Chamberlain and Kalawsky [10] does not appear to report the actual workload values, however does state that the workload was much heavier for the off-table mouse (trackball) than for the stylus with touch screen. In the selection study undertaken by Chamberlain [214] evaluating three pointing devices (the off-table mouse, stylus and trackpad), the workload while standing and using the stylus (with touch screen) was 24.1 and was significantly lower than the trackpad (touchpad) and off-table mouse (trackball) that reported comparably heavier workloads of 46.8 and 47.2 respectively. The results reported by Chamberlain [214] are considerably heavier than the aforementioned workload means found in this study of 14.80 for the touchpad and 29.69 for the trackball. One possible reason may be the brief training session preceding the study undertaken by Chamberlain [214]. Repeated exposure over time was not evaluated

in the study by Chamberlain [214]. In light of this, the results reported by Chamberlain [214] should perhaps be compared against the workload ratings reported in session one of this study, where the touchpad reported 19.56 and trackball reported 42.60. Interestingly the trackball workload rating of 42.60 is similar to 47.2 as reported by Chamberlain [214], however the touchpad workload is less than half of that reported by Chamberlain [214].

The trackball reported the largest drop in workload from session one to session five to marginally less than half of that reported at session one. This finding suggests that participants work harder when not familiar with the trackball even though the trackball reports one of the faster task times and higher throughput values.

The mouse was provided as a benchmark and performed with an overall mean workload of 8.48. Interestingly, the touchpad performed closest to the mouse in terms of workload.

Eleven participants indicated that they would prefer to use the touchpad in a wearable context, while two participants preferred the Twiddler2 and two preferred the trackball (supporting hypothesis 7).

6.7 Conclusion

This chapter has presented an extended usability study evaluating the four pointing devices for use with wearable computers.

Participants' performance improved with the devices given repeated exposure over the course of the five sessions. The rate of improvement differed depending upon the device. Learning stabilised from session 3 onwards with the gyroscopic mouse. The touchpad and trackball performed comparably reaching asymptotic performance from session 4 onwards. Although showing the largest rate of improvement, the Twiddler2 showed no more significant improvement from session 5 onwards. In light of the longer learning curve, the Twiddler2 appears to take longer to learn than the other devices and is perhaps less intuitive in operation. Interestingly, as a benchmark comparison, the table-top mouse showed no significant improvement form session 3 onwards.

All devices demonstrated a significant improvement in performance between session one and session six. In addition, participants performed comparably between session 5 and

session six, i.e. after the retention interval. Interestingly, the Twiddler2 is the only of the four devices to perform with a slower mean task time in session 6 than in session 5 (although not significantly so) perhaps indicating that unless used frequently, is less memorable (i.e. users do not retain knowledge of use) than that of other devices and the user may take longer to re-familiarise herself with the device.

The study confirmed that there is a measurable difference between the wheel (size and distance) combinations presented to participants. Analysis of sessions 5 and 6 reveal that significant differences were found between all wheel combinations excluding wheel combinations of 32 pixels x 300 pixels and 48 pixels x 500 pixels. In light of this, the wheel (size and distance) combinations can be ordered as follows: participants performed fastest while selecting targets that were 48 pixels in size and positioned at 300 pixels apart. Participants performed comparably second fastest while selecting targets of size and distance; 48 pixels x 500 pixels and 32 pixels x 300 pixels. Targets of size 32 pixels placed at a distance of 500 pixels apart were the third fastest. Participants performed the fourth slowest and slowest with target sizes of 16 pixels and distances of 300 and 500 pixels respectively. Analysis of sessions 5 reveals that the participants made significantly more errors with the smallest target size of 16 pixels at both distances (300 and 500 pixels). Analysis of session 6 reveals that wheel condition of 16 pixels x 300 pixels performed with significantly more errors than the others.

The trackball is seemingly the best choice of device for use with any of the target size and distance combinations for use in a wearable context. Similarly, target sizes of 48 pixels positioned at 300 pixels apart is seemingly the best choice for use with any of the pointing devices in a wearable context. The combination of the trackball and the target size/distance combination of 48 pixels x 300 pixels allows for the fastest selection time.

Importantly, this study has shown that Fitts' law applies to the evaluation of the pointing devices in a wearable context (that is, while wearing a computer and a head-worn display). Across sessions five and six, the mean throughput was as follows: Twiddler2 2.30 bps, gyroscopic 2.44 bps, trackball 2.65 bps, touchpad 2.68 bps and mouse 4.87 bps. The trackball and touchpad performed comparably and have a significantly higher throughput than the Twiddler2 and gyroscopic mouse also performing comparably.

The subjective measure of workload provides insights into the usability of an input device within a wearable context. The study confirms that there is a measurable difference in workload when using the pointing devices in a wearable context (supporting hypothesis 6). Across all the sessions, the mean overall workload for the touchpad was 14.80, followed by the Twiddler2 26.97, trackball 29.69 and lastly the gyroscopic mouse 53.64. The gyroscopic mouse is significantly different from the trackball, Twiddler2 and touchpad. The trackball is significantly different from the touchpad. In light of this, a ranking based on overall workload can be established (supporting hypothesis 6) the touchpad has the lightest workload rating, this is followed by the Twiddler2 and the trackball performing comparably with the second lightest workload rating (there is no significant difference reported between the touchpad and Twiddler2 and Twiddler2 and trackball) and lastly the gyroscopic mouse has the heaviest workload.

The next chapter presents wearable pointing device guidelines derived from the four user studies undertaken as part of this dissertation. The guidelines are then used in order to inform the design of a wearable pointing device with novel form factor, the design and implementation are also outlined in the following chapter.

7

Guidelines and Device Development

7.1 Introduction

The four pointing device studies undertaken as part of this dissertation culminate in the production of wearable input device guidelines and recommendations that are presented in this chapter. The guidelines and recommendations are derived from the experimental and qualitative feedback collected from the four usability studies; selection, drag and drop, menu selection and learnability evaluations. The guidelines are applied to the development of a new pointing device with a novel form factor that endeavours to overcome some of the limitations of the pointing devices evaluated in this dissertation. An introduction to the novel pointing device follows the description of the guidelines and recommendations.

7.2 Guidelines and Recommendations

This section provides general guidelines and recommendations to help guide the design and selection of pointing devices suitable for use with wearable computers. These recommendations are derived from the detailed and specific qualitative feedback in addition to the quantitative findings from the four studies presented in this dissertation (evaluating pointing devices within a wearable context). These guidelines and recommendations are designed to provide insight and direction when designing pointing devices suitable for use with wearable computers. While some of these guidelines are not new and for the most part are not surprising, they are derived from the empirical and qualitative evidence of the four wearable studies and therefore provide a foundation upon which to guide the design of wearable pointing devices. Although the guidelines are specific to the design of wearable pointing devices, where appropriate, they may be generalised to influence and guide the design of wearable input devices in the broad. The qualitative evidence was obtained from participants' responses to the following questions: "Were there any aspects of the (device) that made moving the cursor and/or pressing the button to (perform the task) difficult?", "What did you like about using the (device)?", "What did you dislike about using the (device)?", and finally, "Any other comments?"

The guidelines and recommendations are as follows:

Guideline 1:	Allow or encourage interaction in a range of natural positions. *1.1* Promote natural placement of fingers/hands/arms/other (comfortable to hold or comfortable attachment).
Guideline 2:	Ensure cursor stability while mobile. *2.1* Movement of device should not cause unwanted interaction.
Guideline 3:	Minimize body (finger/hand/arm/other) movement required to manipulate the cursor.
Guideline 4:	Button presses should be easy and intuitive. *4.1* Buttons should be suitably spaced so as to not interfere with other buttons or cause accidental button presses. *4.2* Avoid positioning buttons where the device is attached or contacts with the hand.
Guideline 5:	Avoid the interplay between button press and cursor movement.
Guideline 6:	Provide simple interactions to achieve complex functionality.
Guideline 7:	Encourage single handed use if appropriate. *7.1* Consider the effect of arm movements caused by use in motion (two handed use).
Guideline 8:	Ensure the device can be attached stably (attached to body or held in the hand). *8.1* Avoid the use of the other hand to stabilise the device.
Guideline 9:	Facilitate quick access/grasp time for a handheld device.
Guideline 10:	Promote subtle/unobtrusive pointing device and use.
Guideline 11:	Ensure a compact size and light weight device.
Guideline 12:	Encourage eyes free interaction through simple design, operation and functionality.
Guideline 13:	Provide a wireless pointing device.
Guideline 14:	Avoid the use of accelerometers for cursor control if mobile (i.e. walking).
Guideline 15:	Choose user interface components that suit coarse mouse movements.

The above guidelines and recommendations are explored in detail below.

Guideline 1: Allow or encourage interaction in a range of natural positions

Allow or encourage interaction with a pointing device in a range of positions. Some participants preferred that the Twiddler2 could be used in a range of positions, by stating that "when arm was tired you could drop arm to side" and "could hold my hand by my

side and operate it fine, the other devices had to be held up in front of me". The trackball was also "able to have hand anywhere and just use the thumb to move", "can be used in any arm position" and "could drop device to side". Qualitative comments suggest that forcing the hand or arm into specific positions while operating the device should be avoided. A device that can be operated while the hand is held in numerous positions is favourable. This may contribute to reducing the fatigue and effort associated with operating a device in forced positions. For example, some participants found that when using the gyroscopic mouse that there was "no relaxing of the hand during usage", and that "the hand has to remain in a certain (not relaxed) position all the time". Some users also found this to be true of the touchpad reporting; "both hands are in air, without any rest", and "having to hold up both arms to operate it".

In a similar vein, a pointing device should allow natural placement of fingers/hands/arms/other (guideline 1.1) while in use and be comfortable to hold. Comments from participants highlighted the importance of this by reporting that the gyroscopic mouse "fits nicely into the hand". Likewise, highlighting the importance, albeit with unfavourable comments, some participants reported that the Twiddler2 resulted in "awkward finger positions", and that the "finger didn't naturally align with the A or E buttons". In addition, the Twiddler2 was "hard to reach around and click properly", given that the "buttons are in a difficult position". A user found that "holding arm in the same position can be strenuous" while using the touchpad. Although the Twiddler2 could be used in a range of positions, some participants found it to be "not comfortable", "the design of the mouse does not seem ergonomic – making it difficult to hold and operate", "it was uncomfortable to hold", and "no comfortable way of holding the mouse. No comfortable way of pressing the button". Comfort should also be considered in the case of devices attached to the body (guideline 1.1). A comment from a participant suggested he/she disliked "the strap" on the Twiddler2, with another participant stating that "how the strap was attached made a difference to the systems accuracy and usability". This may suggest, as Dunne and Smyth [255] state, that when attention is drawn to the discomfort (un-wearability) caused by a device, that this in turn impacts negatively upon the cognitive capabilities of the user. The guidelines by Gemperle et al. [256] also support the need for comfortable attachment systems.

Guideline 2: Ensure cursor stability while mobile

Given the pointing device may be in use while mobile and stationary, it is important that the mechanics of the device are designed so that user movement (e.g. caused by walking) does not affect cursor movement. The cursor should not involuntarily move as a result of the user's movement. The gyroscopic mouse suffered the greatest in this regard with some users' commenting; "body movement interferes with mouse movement", and the device "moved when you did making it impossible to use when walking". Walking also affected the trackball device with some participants finding that the "ball moves during walking when not desired sometimes". However, the Twiddler2 was found to be "stable during body movement", and "stable/consistent mouse motion during both the walking and stationary experiments". Some participants found that "walking made very little difference to operation" of the touchpad. While others found that "walking movement made my hands shake making the cursor move". However, a probable cause of this may be the interplay of the arms resulting from use in motion (discussed in guideline 7.2) rather than the mechanics of the touchpad.

In a similar vein, movement of a device (e.g. in the hand or on the body) should not cause unwanted interaction (guideline 2.1), that is, involuntary cursor movement or accidental button press. A user of the trackball noted that "if I held the trackball strangely the cursor would move by itself". The Twiddler3 (recently released on the market) makes use of a slight delay of less than 0.5 ms from the time that the user first presses the Nav Stick and when the cursor moves, in an attempt to avoid inadvertent cursor movement caused by accidental bumping of the Nav Stick.

Guideline 3: Minimize body (finger/hand/arm/other) movement required to manipulate the cursor

Minimize movement (fingers/hands/arms/other) required to control/move the cursor on the screen. A participant commented that the "small size of the touchpad overtime requires multiple strokes to move the cursor". Likewise, the trackball required that "when the distance was large, it requires repositioning thumb on ball for a second movement", "the repeated thumb movement to get the cursor from one side of the screen to the other, the other devices really only needed one movement". Some participants favoured the Twiddler2 as "the thumb movement is better than the trackball – one gesture as opposed to a couple". Some participants noted that the gyroscopic

mouse required "too much arm movement", "requires large wrist/arm movements" and "too much arm/wrist motion for simple tasks".

Guideline 4: Button press should be easy and intuitive

Button press should be easy and simple and not increase the effort or force required to operate the device. Some users reported that "the button is required to be pressed a little harder than I would have liked" while using the trackball. Likewise, users of the Twiddler2 reported that "a more sensitive button would be suitable", and that "the button was hard to press". However, some participants reported that the "button was easy to push" on the gyroscopic mouse.

Buttons should be suitably spaced so as to not interfere with other buttons or cause accidental button presses (guideline 4.1). Selection buttons should be positioned for easy and intuitive activation. Some users found that "fingers are slightly cramped on the buttons" and "the buttons were too close" on the Twiddler2 reporting that "many times I pressed the buttons accidently", it was "hard to hold and had to be careful to press the right button", and that there are "too many buttons that can accidently be pressed".

In addition to the above, avoid positioning buttons where the device is attached or contacts with the hand (guideline 4.2). This appears to cause users to expend extra effort to avoid inadvertently registering a mouse click. For example, the "finger has to hold device and press the button simultaneously" when using the trackball. Some users found that "securing the device with a single finger and avoiding excessive pressure from activating the button was a minor learning challenge", and "not being able to rest my index finger on the trigger button without fear of clicking".

Guideline 5: Avoid the interplay between button press and cursor movement

Be mindful of the interplay between button press and cursor movement and vice-versa. Pressing the button should not affect the position of the cursor on screen. That is, a button press should not cause the cursor to move involuntarily. Likewise, moving the cursor should not result in an unwanted button press. Comments from participants reported issues of this nature across all of the devices, for example, the gyroscopic mouse reported, "the highly sensitive nature that even a click for the mouse moves the cursor away from the dot" and "releasing the trigger often caused the mouse to move slightly". When using the trackball, "occasionally when pressing the button I would inadvertently

move the mouse just off the target". Likewise for the Twiddler2, "clicking button and mouse at the same time – would often move the mouse unintentionally", "clicking a button on one side pushes it against my thumb, making the pointer move off the target". The touchpad appeared to suffer the least from this, although one participant reported; "cursor moves when tapping", and another, "when walking, it's easy to accidentally click - tap".

Guideline 6: Provide simple interactions to achieve complex functionality

Avoid having to engage multiple fingers at the same time – this may be especially true for hand held devices. To hold the select button down while moving the cursor proved to be challenging in a wearable context. Comments in this regard stated that the gyroscopic mouse required "too many buttons to press at once", "sending the message to your finger then to your thumb can be quite different and can take a bit of getting used to", "having to keep a button pressed while moving the cursor, I sometimes got confused between having to drag and having to move the cursor", and finally disliked "coordinating – holding two buttons while moving it around". Having to coordinate two simultaneous actions may have contributed to the high workload rating of the gyroscopic mouse. Likewise, some participants reported that they "sometimes found it difficult to keep finger on the trigger while moving the ball" while using the trackball. The Twiddler2 received comments such as "hard to press E key and walk and drag mouse", "difficult to press button and move cursor at same time (device is a little too big) ", "found it difficult to maintain pressure on the A key while using the thumb to move the cursor", "found it difficult to maintain pressure on the A key while using the thumb to move the cursor". Likewise for the touchpad; "trying to hold the button and drag can be rather annoying as it was rather uncomfortable". In light of this, designs should allow for simple interactions that achieve complex actions, for example, the use of only one button to achieve a drag and drop operation. The D key on the Twiddler2 emulates a left mouse button being held down and as a result, is not required to be held down while moving a target. A comment in favour of this reported that the Twiddler2 "was the easiest to use as I didn't have to think about it while I was moving the cursor". A participant suggested of the gyroscopic mouse, "the button to turn it on and off would possibly be better using a switch so you don't have to keep your hand clenched".

Guideline 7: Encourage single handed use if appropriate

If appropriate, discourage engaging the use of both hands while interacting with a pointing device. A recommendation is that one hand be free at all times in order to interact with the user's environment. Indicative comments pertaining to the trackball is "you'd probably be able to do other things whilst it's on your finger". The touchpad however, requires that "two hands are occupied, but if you can afford that, no problems". In addition, attaching a pointing device to the body in a way that facilitates hands free interaction with the user's environment when the device is not in use is recommended. This allows for quick access time as reported by Ashbrook et al. [65], and the user is not forced to put the device away (holstering) while not in use. A participant stated that the touchpad was "at hand without being in hand", and "does not get in the way when not in use".

In the case where a two handed interaction design may be appropriate, consider the effect of dual arm movements caused by use in motion, i.e. walking (guideline 7.1). This was identified by some users of the touchpad finding that the "normal arm motion while walking makes it awkward to use", and "both arms moving while walking meant sometimes finger left the surface".

Guideline 8: Ensure the device can be attached stably (attached to body or held in the hand)

If the device is to be attached to or placed on the body, it is important that interaction with the device does not cause it to move or slip in any way. Similarly, if the device is to be held in the hand, interaction with the device should feel stable, well placed in the hand, and free from movement or chance of slipping. Pressing the button or moving the cursor should not cause the device to move in the hand so as to cause the user to have to reposition it. Users may feel they have a lack of control over the device if it moves around during use or if it appears to be loosely attached to the body. Some users reported that the trackball "moved around when trying to use it" and that "moving cursor was difficult to get used to because it's not very stable". Similarly, the Twiddler2 was "tricky to get the strap adjustment perfect", "very unfirm fitting", "pressing buttons is difficult if device isn’t strapped in completely", and "have to get the right grip otherwise the force of pressing the button can move the whole device". Use of the trackball required users "to remove my thumb from the ball rest it on the side of the device to

stabilise it while I pressed the trigger". The "trackball device is not stable enough for precise control if held only one-handed" and "needed left hand to support right hand while using it". However, one should avoid the use of the 'free' hand in order to stabilise the device (guideline 8.1). If the device is attached to the body, or held in the hand, it is important that the user does not feel the need to use the hand that is not in use in order to stabilise the device. In this respect, the device would be considered a two handed device that does not allow for one hand to be free to interact with the environment (as suggested in guideline 7). For example, some participants reported that when using the Twiddler2 device, that they "have to hold it with my left hand to stabilise the use of the device".

Guideline 9: Facilitate quick access/grasp time for a handheld device

If the device is to be held in the hand, then it is recommended that the design would allow for quick access/grasp time. Ideally, a design that considers and allows for some sort of on body placement (similar to a mobile phone pouch) or allows the repositioning of the device on the body while not in use would be advantageous. In this case, it is recommended that the design would facilitate quick access/grasp time when engaging with the device and likewise would facilitate the quick return when not in use. Ashbrook et al. [65] found that a device placed on the wrist afforded the fastest access time, followed by a device placed in a pocket and lastly devices holstered on the hip had the slowest access time. Rekimoto [64] suggests allowing for the ability to quickly change between holding the device and putting it away should hands-free operation not be supported. Likewise, Lyons and Profita [257] suggest that device placement should allow for ease of access, use and return. Placing or positioning the device on the body should not inadvertently cause device activation (that is, involuntary button press or cursor movement).

Guideline 10: Promote subtle/unobtrusive pointing device and use

A wearable device should be subtle and non-obtrusive and encourage use in a public environment. A comment highlighted this in relation to the trackball; "the size was great if say this type of tech was used in public then it would be easy to pull out without it feeling like you are pulling out a large amount of wires and hardware", that is, input devices that have a low social weight [52, 68]. Suggesting the importance of public and socially aware use, one participant reported that the touchpad is "not very stylish".

Resulting from their work on designing for wearability, Gemperle et al. [256] also recommend unobtrusive placement as an important consideration, in addition to keeping aesthetics in mind. Likewise, Rekimoto [64] suggests that a wearable device should be as unobtrusive and natural as possible in order to be adopted for everyday use. Discrete, private and subtle interaction has also been emphasised in recent work [2, 6] as important in allowing users to act as naturally as possible in a public setting.

Guideline 11: Ensure a compact size and light weight device

The size of the device should be designed to fit the hand of the general user population or provide a means to adjust the device in order to fit a variety of hand sizes. The size and weight of the device should be such that it does not cause extra muscle fatigue or strain while in use. The trackball was favourable for being "compact, non-intrusive", and "small". However, the Twiddler2 "device a little large to control and hold", "bulky controller", and "didn't suit my hand at all, it felt very awkward to use". Devices should be nicely weighted so as to avoid muscle fatigue or strain caused by heavy devices. Some participants preferred the "light weight" nature of the trackball device. Gemperle et al. [256] also found size and weight to be an important consideration.

Guideline 12: Encourage eyes free interaction through simple design, operation and functionality

Given that users may be mobile while wearing a head-worn display, the device should facilitate minimal visual attention, that is, users are not forced to look at the device while in use. The device should be simple to operate and provide appropriate tactile feedback so that users may focus on the task within the wearable domain and minimise looking at the device. Exemplar comments pertaining to the trackball device were; "nice and simple. Comfortable", "easy trigger style click button", and "the trigger button is easy and comfortable to use". Komor et al. [69] suggest that in a mobile setting, the user should be able to expend little to no visual attention in order to access and use an interface.

Guideline 13: Provide a wireless pointing device

Given a wearable/mobile context, input devices are recommended to be wireless in nature so that cords do not interfere with the user's environment or task. The wireless nature of the gyroscopic mouse received favourable comments from participants. While "the wire sometimes got in the way" when using the trackball mouse and similarly when

using the Twiddler2, the "cable got in the way sometimes". One participant disliked the Twiddler2 because "it was connected via wires".

Guideline 14: Avoid the use of accelerometers for cursor control if mobile (i.e. walking)

Accelerometer technology should be avoided as a means to control the cursor if used while walking. The accelerometer is extremely sensitive to vibration noise caused by walking, making the device extremely difficult to use while mobile. As noted in the comments for the gyroscopic mouse, "I had to stop each time I wanted the device to work – very slow walking pace!", "very difficult to control the cursor while walking", and "any movement causes the mouse to react – making the system unusable".

Guideline 15: Choose user interface components that suit coarse mouse movements

Larger components that can be selected (or other interaction techniques) with large coarse movements are preferred, especially if the wearable will be in use while walking (and stationary). Some participants stated that the gyroscopic mouse "felt quite natural for large target selection", that it was "too sensitive with smaller sizes", and the "motion sensitivity really hard to click small buttons without taking finger off the back button (to stabilise pointer)". As a result of evaluating their novel input device, Chan et al. [6] suggest the use of target sizes greater than 1.2mm. The studies presented as part of this dissertation have found that targets that are larger and are closer together can be selected and dragged and dropped faster than targets that are smaller and further away from each other. The results derived from the learnability target selection study and the drag and drop study found that target sizes of 48 pixels placed at a distance of 300 pixels apart are selected and dragged and dropped significantly faster than any other combination, followed by size and distance combinations of 32x300 pixels and 48x500 pixels performing comparably as the next fastest. Target sizes of 16 pixels placed at either 300 pixels or 500 pixels apart were slower and more error prone than the other size and distance combinations. Placement of the interface components should also be a consideration to leverage the ability to utilise coarse mouse movements. The pull down menu reported the second fastest time in the menu selection study. One possible explanation may be that the top and bottom of the screen acted as an impenetrable border, whereby participants were able to make long, coarse movements towards the menu item without overshooting the target.

7.2.1 A Final Comment Regarding the Guidelines and Recommendations

The above guidelines and recommendations are to be treated as such and are by no means designed to be a prescriptive list that purposes to achieve 'the perfect' wearable input device. Quite simply put, they are lessons learned from the numerous evaluations undertaken as part of this dissertation. Drawn from the quantitative and qualitative evidence of the studies, they provide a foundation upon which to begin. The hope is that designers of wearable input devices will be mindful of and be directed by the guidelines. Equipped with the knowledge and insight that the guidelines offer, designers may apply the guidelines that are appropriate to the context of use and the user's requirements. To this end, the guidelines should be examined and appropriated in a way that suits the context and mode of use. Designers may need to weigh the costs and benefits of applying the guidelines and choose those that most meet the users' requirements and their context of use. Starner [61] identifies the need to consider the trade-offs between usability, portability and unobtrusiveness when designing a wearable device. Lyons and Profita [257] advocate the need to adopt a holistic approach when designing a wearable device, that is, both tailoring the design to account for engagement with a device, and also to account for what happens with the device when it is not in use. Dispositions, as termed by the authors [257] represent "both the user pose and the physical relationship between the device and user". Being mindful of the various dispositions of the user, and the transitions between dispositions, empowers designers to factor them into the design of a device in order to better suit the wearable nature of the device.

In addition to guiding the design process, the above guidelines and recommendations may also be used to inform users of wearables by guiding towards the selection of a suitable wearable input device. That is, the guidelines form a checklist that can be utilised as a point of comparison when choosing between different available input devices.

7.3 Device Development

The set of guidelines derived from the four usability studies were applied to build a pointing device with a novel form factor suitable for use within a wearable context (i.e. while wearing a computer and for use with a head-worn display). Under the direction and guidance of the author of this dissertation, the device was both designed and subsequently implemented by a team of people[47] (studying and/or working at the University of South Australia). The new wearable pointing device with novel form factor is depicted in Figure 57. According to Calvo and Perugini's [258] characterisation, the pointing device has a hand-operated control mechanism, an electromechanical sensing mechanism, and a body-mounted form factor.



Figure 57: Pointing device with novel form factor (front and back)[48]

[47] Wynand Marais was responsible for designing and building the technical package (electronics and software) housed in the shell of the device. Wynand Marais and Robert Kong Win Chang implemented subsequent small modifications to the technical package (electronics and software) in order to resolve implementation challenges. Ben Neal worked on the design of the device (form factor) and produced SolidWorks models suitable for 3D printing and presentation.

[48] Used with permission of Ben Neale.

The use of an optical sensor as the control mechanism for cursor movement was inspired by the work of Hwang et al. [140] producing a wrist mounted input device consisting of an optical sensor (outperforming a joystick when evaluated) and the DJammer [259, 260] a wearable musical instrument that used an optical sensor to control scratching.

An important design consideration was a wearable pointing device that is subtle, unobtrusive in form factor and allows interaction via discrete, understated movements; that is, a socially acceptable device that feels appropriate for public use (guideline 10). To this end, the device is compact in size and light in weight (guideline 11), currently weighing 22 grams.

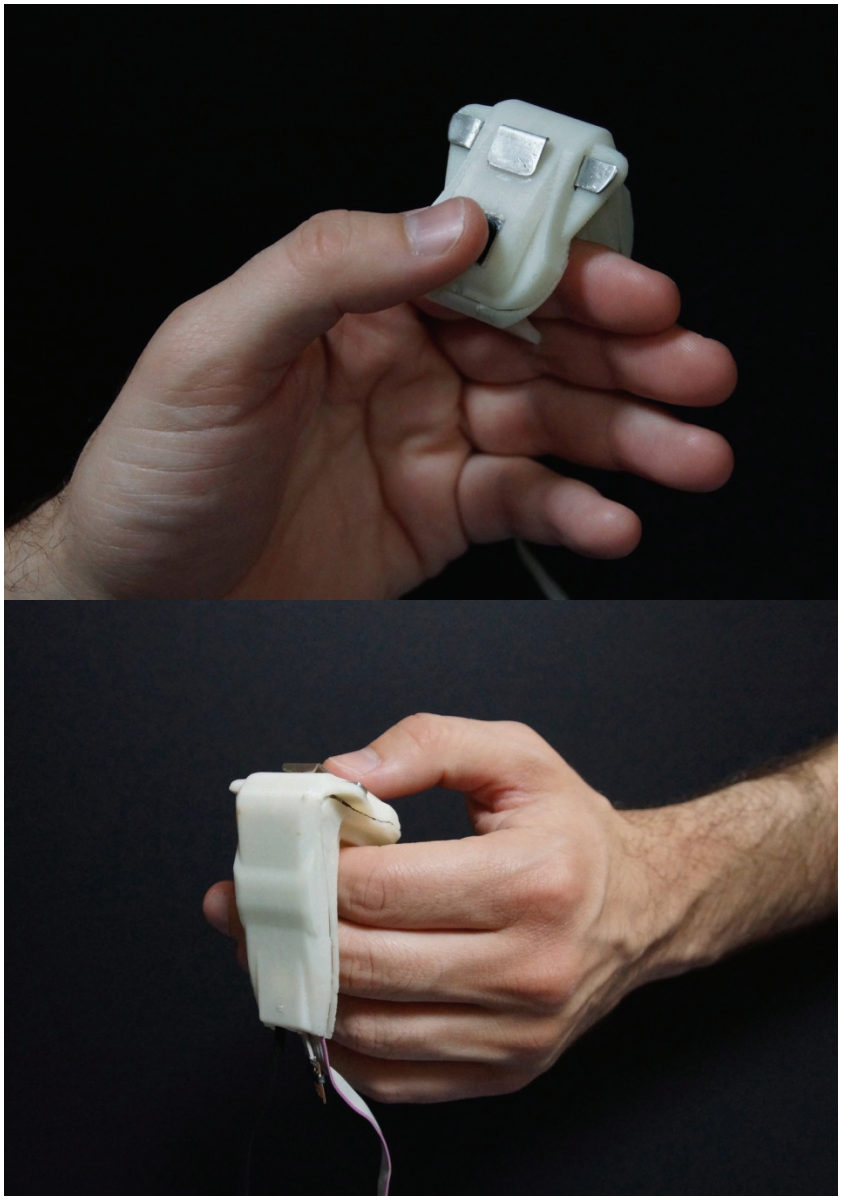


Figure 58: Pointing device positioned on the hand

Although the guidelines recommend a preference for wireless devices (guideline 13), for the first iteration of the device, a thin black cable is used to connect the device to the computer via USB (the grey cable depicted in Figure 58 is used for programming purposes only). A wireless version of the device is planned for the next iteration of the device.

The wearable pointing device is designed to be worn on the user's index finger and runs down the back of the user's hand. The device positioned on the hand is illustrated in Figure 58. The grip is designed to be detachable to allow for the use of differing grip sizes in order to accommodate the variety of finger/hand sizes, and in turn, ensuring that the device can be stably attached to the hand (guideline 8). The aim is to have the grips made out of a rubber that will allow the grip some flex; doing so will also ensure that a variety of finger/hand sizes are accommodated and that firm, stable attachment to the hand is facilitated. In addition to the grip being positioned in front of the index finger, the device also runs down the back of the user's hand, both of which work together to facilitate a stable attachment (guideline 8). The device is positioned on the hand in such a way as to allow hands free interaction with the environment when the device is not in use and single handed interaction when in use (guideline 7). In light of this, the device facilitates a short access time (guideline 9) as it is designed to be worn continuously attached to the hand.

As demonstrated in Figure 58, the hand is held in a natural position in order to interact with the device, and may also be operated while the hand is held in numerous positions (guideline 1). Cursor movement is via subtle thumb movements (guideline 10) performed over an optical mouse sensor as depicted in Figure 58. Multiple movements with the thumb may be required however, given the small footprint of the device and depending upon the distance being moved. Button press is via capacitive buttons (silver items depicted in Figure 58). The capacitive buttons require a light touch, which were designed to minimize the amount of movement of the device in the hand as a result of a button press (guideline 8). The optical sensor also requires a light touch, minimising the amount of movement of the device in the hand (guideline 8). The button positioned in the middle of the device functions as left click, and the button on the right functions as right click. In order to avoid having to engage the use of two fingers to perform a complex action (i.e. pressing left click while attempting to move the cursor as required in a drag and drop operation), the button on the left functions as a left mouse click being held down

(guideline 6), that is, click and hold (pressing the button toggles it on and off). The optical sensor and buttons are suitably spaced so as not to interfere with each other (guideline 4) and there should be no interplay between button press and cursor movement (guideline 5). There are no moving mechanisms on this device therefore moving the device should not cause unwanted interaction such as involuntary cursor movement or accidental button press (guideline 2). In addition, the cursor should therefore remain stable (guideline 2) while in use and while mobile (i.e. walking with the device).

The device aims to provide simple and intuitive interaction without the need for sustained visual attention while in use (guideline 12), or at most, will require minimal glancing.

A similar commercially available product has recently appeared on the market called the Genius ring presenter/mouse[49]. The mouse can be toggled into presentation mode for use with slides and can also be used in mouse mode. The Genius ring mouse is wireless, worn on the index finger and as suggested by the name, is ring shaped. Users interact with the device using their thumb. An optical touch sensor is located in the middle of the device for cursor control. The sensor can also be pressed to perform a left click operation. Four buttons are placed around the sensor. To the left of the sensor, the button toggles between cursor and scroll modes, and positioned to the right of the sensor is the right click button. The button positioned on the bottom performs a back page operation, while the top button toggles drag/move operations. A few subtly different versions of the ring mouse have been released by Genius.

The original version of the Genius ring mouse was released shortly after the new pointing device designed as part of this dissertation was completed (although subsequent iterations were required to make subtle changes to the finger grips and to the housing in order to properly fit the technical package; iterations were also required to make small changes to the technical package in order to fix implementation errors and problems as they arose). While both devices perform cursor control, left click, right click, drag/move operations, are controlled by using the thumb and are worn on the index finger, they differ in form factor. The way the devices attach to the index finger differ, the Genius mouse has a partially closed rubber ring which is designed to be slipped onto the finger,

[49] http://www.geniusnet.com/

much like a normal ring. The device presented in this dissertation however, runs down the back of the user's hand and has a grip that is positioned in front of the index finger, both of which are contoured and work together to ensure the device is stably attached to the hand. The rubber ring on the Genius mouse is a little on the larger side and is most likely too large for smaller hand sizes; there is unfortunately no way to adjust the size of the rubber ring. The optical sensor in the Genius mouse is positioned slightly off centre (vertically) and toward the top of the device, which contrasts the device presented in this chapter that places the sensor toward the bottom of the device. The buttons surround the sensor on the Genius mouse, whereas the buttons run along the top of the device presented in this chapter. In addition, the Genius mouse makes use of push buttons instead of capacitive buttons as per the device presented. The positioning of the drag/move and left click buttons differ. The drag/move button is positioned at the top of the Genius device, however it is placed on the left side of the device presented in this dissertation. The left click button is placed at the centre top (above the sensor) of the device presented in this chapter, however it is positioned under the sensor on the Genius mouse.

The commercial release of the Genius ring mouse and its variations is encouraging given that over the course of this dissertation, new commercially available pointing devices suitable for use with wearable computers have been limited, if not non-existent. Encouragingly, the design of the device lends itself to some of the guidelines and recommendations presented in this chapter.

7.4 Conclusion

This chapter has presented the guidelines and recommendations derived from four usability studies undertaken and presented in this dissertation. As an exemplar of the application of the guidelines and recommendations, a pointing device with novel form factor is designed and described. The next chapter concludes the dissertation with a summary of the findings of the usability studies. The summary provides valuable information pertaining to the pointing devices and may assist in guiding and informing users when choosing between pointing devices suitable for use in a wearable context.

Factors to consider when selecting a wearable pointing device:

- Task: How will the user interact with the wearable computer, that is, what are the typical interaction tasks required?
- Mobility: Will the user be mobile or stationary or will a combination of mobility conditions be employed?
- Speed of operation: Does the user need to perform efficiently, that is, perform tasks quickly?
- Level of precision required: Does the user need to perform precisely (i.e. precise movements)?
- Level of accuracy: Does the user need to perform effectively, that is, perform tasks accurately?
- Hand held or body worn device: Does the user require that two hands be free or one? Does the user require fast access to the device and likewise, fast return when not in use? What will happen with the device when it is not in use? [257].

8

Conclusion and Future Work

8.1 Introduction

The exploration of wearable human-computer interaction is an important and necessary field of study. Research into effective input devices and user interfaces for wearable computers is critical to the usability and adoption of a wearable system. In spite of the need to better understand wearable interaction, there has been very little work evaluating pointing devices available in the marketplace suitable for use with wearable computers. Section 2.6 highlights the lack of empirical studies that evaluate pointing devices in a wearable context, that is, studies that require the participant to don a wearable computer. Of the limited literature reporting results evaluating a participant while wearing a computer, only two of the studies employ a binocular head-worn display. The other studies described in Section 2.6 make use of a vest worn fold-down screen (target selection [10, 143, 214], drag and drop [214] and trajectory based [214] tasks); a monocular head-worn display (text entry [218] and menu interaction [9] tasks); and a binocular head-worn display [150-152]. Of the two studies that report results evaluating participants while wearing a computer and a binocular head-worn display, one study evaluates appropriate device placement [151, 152] while the other study investigates a novel selection interaction technique [150]. As evidenced, literature pertaining to the evaluation of commercial pointing devices in a wearable context (wearing a computer and a binocular head-worn display) is limited. Amidst the growing interest in input devices [1, 4, 6] and interaction techniques [2, 7] suitable for use with head-worn displays, the limited number of empirical studies available in this space highlights the importance of exploring wearable human-computer interaction. This dissertation presents contributions to the field of wearable human-computer interaction motivated by the need to address the existing gap in knowledge.

8.1.1 Contributions

The contributions presented in this body of work can be summarised as follows:

- *A systematic formal evaluation of commercially available pointing devices in a wearable context, that is, while wearing a computer and binocular head-worn display.* The body of work presented in Chapters 3 - 6 [134, 226, 254] of this dissertation has explored commercial pointing devices available for use within a wearable context via a systematic evaluation over a suite of three different tasks

and by means of an extended learnability study. The results of the studies quantify and provide an understanding of the use of commercially available pointing devices in a wearable context. The usability studies were designed in order to provide answers to the following research questions:

- Whether there is a measurable difference between the pointing devices in a wearable context.
- Whether a ranking can be established pertaining to the use of the devices in a wearable context.
- Whether certain devices are better suited to certain task(s) and/or mobility condition(s).
- Whether there is an optimal pointing device in terms of operator performance over a suite of tasks and mobility conditions.
- Whether users have a preference of pointing device.

The empirical and qualitative results derived from the studies presented in Chapters 3 – 6 (inclusive):

- provide information to the wearable computing research and industry community regarding the performance of the devices in a wearable context;
- provide valuable information regarding the usability of the devices that will guide users in selecting a pointing device that is well suited and appropriate for a task(s) in a wearable context; and
- provide a set of metrics by which future wearable devices can be compared against, for example, the measure of throughput.

- *A set of guidelines and recommendations presented in Chapter 7 grounded on experimental and qualitative evidence derived from the four usability studies undertaken as part of this dissertation.*

- *A pointing device with novel form factor (detailed in Chapter 7) for use within a wearable context as an exemplar of the application of the guidelines and recommendations.*

This chapter revisits each of the research questions in turn and provides summaries for each question across the results of the four usability studies. The chapter provides final remarks pertaining to the guidelines and recommendations and novel pointing device. A

discussion of the limitations of the work and a look toward future work directions concludes the chapter.

8.2 Research Questions

The following section revisits each of the research questions in light of the findings of the four usability studies presented in this dissertation.

8.2.1 Measurable Difference and Ranking of Pointing Devices

The studies presented in this dissertation confirm that there is a measurable difference between the pointing devices and that a ranking can be established pertaining to the use of the devices in a wearable context. Table 43 and Table 44 provide a visual summary of pointing device performance for each of the four interaction tasks undertaken as part of this dissertation. The tables are broken up into standing and walking mobility conditions and the solid black lines placed between the devices are to indicate their separate groupings in order to communicate ranking.

Table 43: Summary of device ranking for each usability study (time)

Time	Target selection	Drag and drop	Menu selection two-level	Learnability
Faster	Gyroscopic	Gyroscopic	Trackball	Trackball
Standing	Trackball	Trackball	Touchpad	Touchpad
	Twiddler2	Touchpad	Gyroscopic	Gyroscopic
Slower		Twiddler2	Twiddler2	Twiddler2
Faster		Trackball	Trackball	
Walking		Touchpad	Touchpad	
		Twiddler2	Twiddler2	
Slower		Gyroscopic	Gyroscopic	

Table 44: Summary of device ranking for each usability study (error)

Error	Target selection	Drag and drop	Menu selection two-level	Learnability
Lower Standing Higher	Trackball Twiddler2 Gyroscopic	Gyroscopic Touchpad Twiddler2 Trackball	Trackball Twiddler2 Touchpad Gyroscopic	Twiddler2 Touchpad Trackball Gyroscopic
Lower Walking Higher		Touchpad Twiddler2 Trackball Gyroscopic	Trackball Touchpad Twiddler2 Gyroscopic	

8.2.1.1 Target Selection Study

The results derived from the target selection study presented in Chapter 3 [226] found that the gyroscopic mouse facilitated the fastest selection of targets. The trackball ranked second, with the Twiddler2 performing the slowest for target selection tasks. The trackball was significantly more accurate than the other devices. The Twiddler2 and gyroscopic mouse ranked comparably second for accuracy (no significant difference was found between this pair).

8.2.1.2 Drag and Drop Study

As identified in the study presented in Chapter 4 [134], the gyroscopic mouse was most efficient at dragging and dropping targets while stationary. The trackball and touchpad ranked comparably second, while the Twiddler2 performed drag and drop operations the slowest. The gyroscopic and touchpad mouse most accurately drag and dropped targets, while the Twiddler2 and trackball were the least accurate (a significant difference was found between the gyroscopic mouse and trackball only for missed dropped locations, no other significant difference was noted).

Interacting while walking highlighted the trackball and the touchpad as performing comparably the fastest, the Twiddler2 ranking second, while the slowest device was

found to be the gyroscopic mouse. The Twiddler2 and touchpad devices were most accurate at executing the dragging and dropping of targets in the walking experiment, the trackball the next accurate, while the gyroscopic mouse was least accurate (no significance was found between the Twiddler2 and touchpad; in addition, no significant difference was reported between the Twiddler2 and trackball for missed dropped locations).

8.2.1.3 Menu Selection Study

The results derived from the two-level menu selection study presented in Chapter 5 [254] identified that two-level menus were selected the fastest when using the trackball while standing. The touchpad and gyroscopic mouse resulted in comparably the second fastest times, while the Twiddler2 performed the least efficiently (a significant difference was found between the trackball and gyroscopic mouse, and trackball and Twiddler2 pairs). The trackball led to the most accurate selection of menu items, followed by the Twiddler2 and Touchpad performing comparably second. The gyroscopic mouse suffered the highest error rate (a significant difference was found when comparing the gyroscopic mouse with the trackball and the Twiddler2 mouse).

While walking, the trackball was the fastest device, followed by the touchpad and Twiddler2 ranked comparably second (no significant difference between this pair), resulting in the gyroscopic mouse placed last. The walking task time rankings mirror those of the walking speed rankings (seen in Table 45). The trackball performed with the least amount of errors, followed by the touchpad and the Twiddler2. The gyroscopic mouse performed with significantly more errors than the other devices.

Table 45: Summary of walking speed (menu selection task)

	Walking speed Menu selection
Faster	Trackball
Device	Touchpad
	Twiddler2
Slower	Gyroscopic

As depicted in Table 45, the trackball had the least impact on walking speed, allowing participants to walk closest to their preferred walking speed (47.28% of their PWS) while performing menu selection tasks. The Twiddler2 (43.87%) and the touchpad (43.66%) ranked comparably second. Participants walked the slowest when using the gyroscopic mouse (31.56% of their PWS), thus the device ranked last.

8.2.1.4 Learnability Study

Results pertaining to the selecting of targets derived from the learnability study (undertaken while stationary only) presented in Chapter 6 indicate that as the sessions progress, there is a banding of the devices as follows; the trackball and touchpad devices are comparably faster than the gyroscopic mouse and Twiddler2 (seen in Table 43; although no significant difference is found between the devices at session five, session six indicates a significant difference between the gyroscopic and touchpad, touchpad and Twiddler2, and trackball and Twiddler2 pairs). The gyroscopic mouse was significantly the least accurate device, while the Twiddler2, touchpad and trackball performed with fewer errors (seen in Table 44).

Table 46: Summary of device rankings for usability measures (learnability study)

Usability Measures	Learnability Learnability Study	Throughput Learnability Study	Workload Learnability Study
Better	Gyroscopic	Touchpad	Touchpad
Device	Touchpad	Trackball	Twiddler2
	Trackball	Gyroscopic	Trackball
Worse	Twiddler2	Twiddler2	Gyroscopic

Performance stabilised from session 3 onwards with the gyroscopic mouse. The touchpad and trackball performed comparably, reaching asymptotic performance from session 4 onwards. The Twiddler2 showed no significant improvement from session 5 onwards. This is presented in Table 46. Participants demonstrated the largest rate of improvement when using the Twiddler2 and trackball devices. The gyroscopic mouse and the touchpad reported the least amount of improvement over the sessions. The longer learning curve indicates that the Twiddler2 takes more time to master than the other

devices and is perhaps less intuitive in operation. It may take longer to re-familiarise oneself with the Twiddler2 after a period of non-use (that is, it may be less memorable than the other devices).

An important result derived from the study is that Fitts' law applies to the evaluation of the pointing devices in a wearable context. As seen in Table 46, the touchpad and trackball performed comparably and have a significantly higher throughput than the gyroscopic and Twiddler2 mouse, also performing comparably. Therefore, the touchpad and trackball devices can be ranked first followed by the gyroscopic and Twiddler2 devices ranking second for throughput.

An assessment of workload found that the touchpad has the lightest workload rating, followed by the Twiddler2 and the trackball performing comparably with the second lightest workload rating (there is no significant difference reported between the touchpad and Twiddler2, and Twiddler2 and trackball). The gyroscopic mouse has the heaviest workload (outlined in Table 46).

8.2.2 Pointing Device Task and Mobility Suitability

The studies presented in this dissertation confirm that certain devices are better suited to certain task(s) and/or mobility condition(s). In the selection study [226] presented in Chapter 3, the gyroscopic mouse was the fastest, least accurate device. In the drag and drop study [134] presented in Chapter 4, the gyroscopic mouse was the fastest and most accurate device while stationary. Although performing a drag and drop operation is a more complex task than target selection, it is interesting to note that the drag and drop findings correlate to the results of the selection study. The results obtained from the two studies seemingly make the gyroscopic mouse a suitable choice when both interaction models (selection and drag and drop) are required (and the user is to remain stationary while using the device). However, the results obtained from the third user study evaluating menu selection [254] presented in Chapter 5, suggest that the gyroscopic mouse is a less suitable choice when precise menu selection is needed, such as the steering necessary for the linear pop-up menu. Results from the fourth user study presented in Chapter 6, found that the performance of the gyroscopic mouse suffers with target sizes of 16 pixels (for both distance conditions). The gyroscopic mouse seems to favour coarse mouse movements, therefore it may be a suitable choice if used in conjunction with interface

objects that allow for coarse mouse movements, for example, a pie menu. The gyroscopic mouse was comparably placed second when performing menu selection tasks. Interestingly, repeated exposure over time (by means of an extended learnability study) resulted in the gyroscopic mouse reporting a slower task time and the highest error rate while completing selection tasks. The difference in results pertaining to the gyroscopic mouse found in the learnability study and that of the target selection study may be due to the varying degrees of task difficulty used in the learnability study (i.e. task difficulty differences due to a range of target sizes and distances used). The task difficulty used in the first selection study was similar to that of targets of 48 pixels in size, placed at 300 pixels apart. This target size and distance combination is perhaps suited to the gyroscopic mouse, given that it tends to favour coarse mouse movements. As noted in the learnability study, the gyroscopic mouse performed faster when target sizes of 48 pixels were used (in either the 300 or 500 pixel distances) and performed comparably with the trackball in this scenario (reporting one of the faster times in the learnability study). Although the drag and drop study presented the same target sizes and distances to participants, the gyroscopic mouse performed the fastest and with the least amount of errors in the standing condition. This may be due to the short learning curve as revealed by the learnability study; participants perhaps were more proficient with the device in a shorter time period which may suggest that the gyroscopic mouse is a suitable choice if novice, intermittent use is required.

The gyroscopic mouse is not suitable for use while walking as it was found to be the slowest and least accurate device while used in this condition (for both drag and drop and menu studies). Participants were noticed to slow down considerably while walking with the gyroscopic mouse. Results pertaining to walking speed in the menu selection task found that the gyroscopic mouse caused participants to walk the slowest at 31.56% of their preferred walking speed while using the device. This is unsurprising given that the inertial sensing technology in the gyroscopic mouse is sensitive to vibration noise, making the device very difficult to use while walking.

The Twiddler2 reported the slowest times and one of the second lowest error rates for all tasks while stationary. While walking, the Twiddler2 was found to perform with the second fastest time for drag and drop tasks and one of the second fastest times for menu selection tasks. The Twiddler2 performed with one of the lower error rates in both

walking tasks (drag and drop and menu selection studies) and in the learnability study. The longer learning curve identified in the learnability study suggests that it may take some time for participants to become comfortable and familiar with the isometric nature of the trackpoint. Some reported that the trackpoint was difficult to "get right" as it was necessary to coordinate moving the thumb off of the trackpoint before pressing a button on the front of the device. However some participants reported that cursor movement was relatively stable when walking. In light of this, the Twiddler2 may be a preferred choice when stable and accurate use is a requirement over speed of use.

The trackball was the fastest and most accurate device while stationary when performing menu selection tasks, and was the second fastest device in the selection and drag and drop tasks. The trackball reported the lowest error rate performing target selection tasks, however it was one of the most error-prone devices when performing drag and drop tasks. The touchpad reported one of the second fastest times when performing drag and drop and menu selection tasks, and one of the faster selection times in the learnability study. In the drag and drop study, the trackball and touchpad were comparably the fastest devices while walking. These findings along with similar findings in the menu selection study seemingly make the trackball or touchpad a suitable choice for use in a wearable context over all the interaction models (selection, drag and drop and menu selection), and over both mobility conditions (standing and walking).

8.2.3 Optimal Pointing Device

The synthesis of results obtained as a result of the body of work presented in this dissertation assists with determining whether there is an optimal pointing device in terms of operator performance over a suite of tasks and mobility conditions. Table 47 represents a summary of the pointing devices across all tasks, usability measures and mobility conditions. The table is colour-coded, with green representing the device that ranked first, orange ranked second and red ranked third for each criterion evaluated (and presented in the table). Usability measures of time, error, user preferences, learnability, walking speed and workload associated with each of the devices are presented for each of the tasks (where applicable) and for both of the mobility conditions. As described in the preceding Section 8.2.2 and illustrated in Table 47, the trackball and touchpad devices are seemingly a suitable choice for use in a wearable context over all the suite of tasks

(selection, drag and drop and menu selection), and over both mobility conditions (standing and walking).

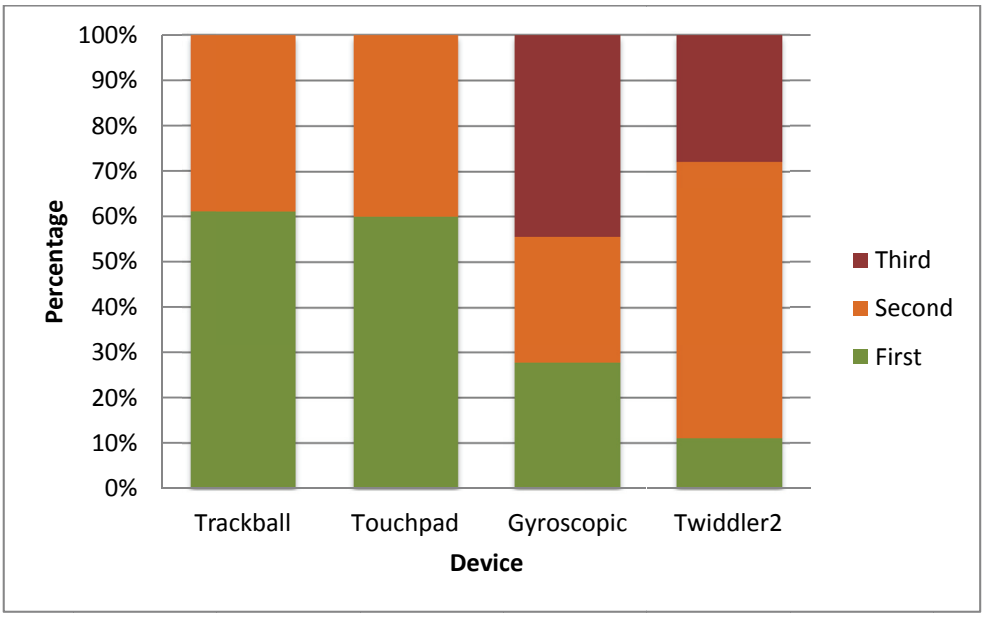


Figure 59: Pointing device summary across all tasks, usability measures and both mobility conditions. Summary of Table 47

Table 47: Pointing device summary. Green represents a first ranking, orange a second ranking and red represents being ranked third. The column headings: Sel, Drag and Menu represent the tasks: target selection, drag and drop and menu selection respectively. The other measures are: learning, walk and work, representing the learnability, walking speed and workload associated with the devices

	Time			Error			User Preference			Other measures		
Standing	**Sel**	**Drag**	**Men**	**Sel**	**Drag**	**Menu**	**Sel**	**Drag**	**Menu**	**Learning**	**Walk**	**Work**
Trackball												
Touchpad												
Gyroscopic												
Twiddler2												
Walking												
Trackball												
Touchpad												
Twiddler2												
Gyroscopic												

A noted disadvantage of the touchpad over the trackball is the need to use two hands for input. Although it is possible to place the touchpad in a number of different positions on a person's body [151], it is recommended that it be placed in a position that minimises

the effect of the movement of the body while walking. Wrist and arm fatigue are also problems with the touchpad device as participants are required to hold their arms in front of them while operating the device. Given that both arms are in front of the participant, the natural movement of the arms while walking may affect interaction. Qualitative feedback suggests that the trackball allows a more natural posture, given that the hand is able to be held in numerous positions, i.e. the arm can be placed naturally by the user's side and not forced into a particular position. Some feedback also indicated that participants preferred to occupy only one hand (as opposed to two) while interacting with a wearable computer.

The trackball appears to be the preferred choice for use in a wearable context while walking and it enabled participants to walk closer to their preferred walking speed while in use. Perhaps one of the reasons that the trackball is the preferred choice is because the ball allows for fast coarse movements to targets, also allows the somewhat seamless change from coarse, fast movements to slow accurate movements. However, some participants reported that holding the trigger button while moving a target in order to perform a drag and drop operation was difficult and exacerbated by walking. For activities that do not involve sustained use (given that fatigue may be a problem), the touchpad is also a favourable choice for use in a wearable context. A noted advantage of the touchpad over the other devices is that it allows both hands to be free to interact with the user's environment when the device is not in use. That is, given the attached nature of the device, the user is not forced to consider putting the device away or manoeuvring it out of the way while not in use. The touchpad also reported the lightest workload over the other devices.

Qualitative feedback indicated that participants found the Twiddler2 to be more natural to use as their hand was able to be held in any position. Participants liked the idea of an isometric joystick for cursor-control; and found cursor movement to be relatively stable while walking. However, it may take some time for users to familiarise themselves with the isometric nature of the trackpoint (the long learning curve identified in the learnability extended study presented in Chapter 6 is perhaps evidence of this). Participants also needed to learn to either remove their thumb before making a selection, or to apply pressure with a different part of the hand so as to not use the thumb. This was due to the fact that selecting targets by pressing a button on the front of the device

would cause the cursor to move if the participant's thumb was positioned on the trackpoint. The biggest challenge facing the Twiddler2 is its form factor with some written feedback requesting an improvement in this area. The Twiddler2 reported a higher level of finger fatigue than the other devices. A more ergonomic design, perhaps in the way of the trackball device, would see a more favourable response by participants and possibly better performance.

The gyroscopic mouse seems to favour coarse mouse movements, as found in the target selection study (Chapter 3) [226], the standing condition of the drag and drop study (Chapter 4) [134], the menu study (Chapter 5) [254] and the learnability study (Chapter 6), and is a less suitable choice when precise movements are required. Fatigue, namely wrist and arm was identified to be a problem with the gyroscopic mouse. The significant challenge faced by users of the gyroscopic mouse is that the inertial sensing technology is sensitive to vibration noise, which in turn makes the device difficult to use while mobile.

Figure 59 depicts a visual summary of table 46, representing as a percentage the combined results across all tasks, usability measures and both mobility conditions for each device. The trackball and touchpad devices are depicted as performing comparably. In light of this and the above discussion, there may not be an optimal pointing device per se, rather, a range of suitable devices each with their own strengths and weaknesses. Armed with the knowledge and insight derived from the studies presented in this dissertation, users may weigh the costs and benefits accordingly and choose the device that best suits their usage requirements and context of use.

8.2.4 Users' Preference of Pointing Device

The studies presented in this dissertation confirm that users have a preference of pointing device(s). Table 48 provides a visual summary of users' preference of pointing device ascertained by means of a survey for each of the interaction tasks undertaken as part of this dissertation. Across all studies except the target selection study, participants prefer the touchpad and trackball devices over the other two. In the selection study, participants prefer the gyroscopic and trackball mouse.

Table 48: Summary of users' preference of pointing device (survey)

Survey	Target selection	Drag and drop	Menu selection	Learnability
Easy Standing Difficult	Gyroscopic Trackball Twiddler2	Touchpad Trackball Gyroscopic Twiddler2	Trackball Touchpad Twiddler2 Gyroscopic	Touchpad Trackball Twiddler2 Gyroscopic
Easy Walking Difficult		Touchpad Trackball Twiddler2 Gyroscopic	Trackball Touchpad Twiddler2 Gyroscopic	

8.3 Wearable User Interface Components

The results obtained from the drag and drop, menu selection and learnability studies also provide valuable insights into the interface components that are efficient and effective within a wearable context. Table 49 and Table 50 provide a visual summary of the performance of interface components (menu items, and target size and distance combinations) for the drag and drop, menu selection and learnability studies. The tables are broken up into standing and walking mobility conditions and the solid black lines placed between the interface components are to indicate their separate groupings in order to communicate ranking.

8.3.1 Drag and Drop

The results derived from the drag and drop study presented in Chapter 4 found that target sizes of 48 pixels placed at a distance of 300 pixels apart are dragged and dropped significantly faster than any other combination, followed by size and distance combinations of 32x300 pixels and 48x500 pixels performing comparably as the next fastest. The third and fourth times were reported by target and distance combinations of 32x500 pixels and 16x300 pixels respectively. Finally, target sizes of 16 pixels placed at a distance of 500 pixels apart were dragged and dropped the slowest. These results are mirrored in the learnability target selection study. As evidenced, it takes longer to complete a task as the difficulty of the task (i.e. index of difficulty) increases [175], that is,

either by decreasing the size of the target and/or increasing the distance between the targets. Targets that are larger and are closer together can be dragged and dropped faster than targets that are smaller and further away from each other. Target sizes of 16 pixels placed at either 300 pixels or 500 pixels apart were more error-prone than the other size and distance combinations.

Table 49: Summary of interface components (time). Target sizes are 16, 32 and 48 pixels and distances are 300 and 500 pixels, i.e. 16 x 500 represents a target size of 16 pixels placed at 500 pixels apart

Interface Time	Drag and drop	Menu selection two-level	Learnability
Faster	48 x 300	Pie pop-up	48 x 300
	48 x 500	Pull down fixed	48 x 500
	32 x 300	Linear fixed	32 x 300
Standing	32 x 500	Linear pop-up	32 x 500
	16 x 300		16 x 300
Slower	16 x 500		16 x 500
Faster		Pie pop-up	
		Pull down fixed	
		Linear fixed	
Walking		Linear pop-up	
Slower			

8.3.2 Menu Selection

The results derived from the menu selection study presented in Chapter 5 found that for two-level menus, pie pop-up menus were selected the fastest when standing, followed by the pull down fixed ranked second, and the linear fixed and the linear pop-up menus ranked third performing comparably (no significant difference could be identified for this pair). The pie pop-up menu performed with the fewest errors, followed by the linear pop-up, pull down fixed, and lastly the linear fixed (all differences were significant). While walking, two-level menus were selected the fastest with the pie pop-up, followed by the pull down fixed ranked second, and the linear fixed and the linear pop-up menus

ranked third performing comparably (no significant difference could be identified for this pair). The pie pop-up and linear pop-up menus performed comparably and with significantly fewer errors than the pull down fixed and linear fixed menus (also performing comparably). The fastest menu over all the devices in a wearable context and across both mobility conditions is the pie pop-up, while the slowest are the linear fixed and the linear pop-up menus. The precise steering necessary to select a sub-menu in the linear pop-up makes it a poor choice while walking.

Table 50: Summary of interface components (error). Target sizes are 16, 32 and 48 pixels and distances are 300 and 500 pixels, i.e. 16 x 500 represents a target size of 16 pixels placed at 500 pixels apart

Interface Error	Drag and drop	Menu selection two-level	Learnability
Lower	48 x 300	Pie pop-up	48 x 300
	48 x 500	Linear pop-up	48 x 500
Standing	32 x 300	Pull down fixed	32 x 300
	32 x 500	Linear pop-up	32 x 500
	16 x 300		16 x 300
Higher	16 x 500		16 x 500
Lower		Pie pop-up	
		Linear pop-up	
Walking		Pull down fixed	
		Linear fixed	
Higher			

8.3.2.1 Top-Level (single-level) Menu Selection

Analysis of the results derived from the menu selection study found that for single-level (top-level) menus while standing and walking, the pull down menu outperformed the other menu structures. The linear fixed and the pie pop-up performed comparably second (no significant difference was found for this pair), and the linear pop-up was the slowest of the menu structures (in addition, the pie pop-up and linear pop-up were not significantly different in the standing condition only). In the standing condition, the pull down fixed and

the linear fixed menus performed with fewer errors than the pie pop-up and linear pop-up menus (although no significance was found for any of the pairs in the standing condition). The menu structures for the walking condition can be ordered as follows: linear pop-up, pull down fixed, linear fixed, pie pop-up (a significant difference found between the linear pop-up and pie pop-up pair only).

8.3.3 Learnability

The results derived from the extended learnability study presented in Chapter 6 found that targets of 48 pixels in size and positioned at 300 pixels apart were selected the fastest. Participants performed comparably second fastest while selecting targets of the following size and distance combinations; 48x500 pixels and 32x300 pixels. Target size of 32 and distance of 500 pixels was the third fastest. Not surprisingly, participants performed the slowest with target sizes of 16 pixels under both distances (performing the fourth and fifth slowest with distances of 300 pixels and 500 pixels respectively). Analysis of session 5 reveals that the participants made significantly more errors with the smallest target size of 16 pixels and at both distances (300 and 500). Analysis of session 6 reveals that targets of size 16 pixels placed at 300 pixels apart resulted in significantly more errors than the others.

8.4 Combined Devices and User Interface Components

A combination of pointing devices and user interface components are summarised in Table 51 (only studies reporting an interaction between pointing devices and interface objects are presented). Menu structures are summarised over both movement conditions (standing and walking) and target selection is summarised based on the results of the learnability study (evaluating participants while stationary). Green shading represents a first ranking, orange represents being placed second and red depicts a third ranking. The darker shading indicates faster times and the lighter shading portrays slower times (typically moving left to right).

As depicted in the summary presented in Table 51, the trackball is seemingly the best choice of device for use with any of the menu structures, and target size and distance combinations. The pie pop-up menu (two-level), the pull down menu (single-level) and

targets of 48 pixels in size and positioned at 300 pixels apart are the best choice of interface components for use with any of the pointing devices in a wearable context.

The combination of the trackball and the pie pop-up menu allows the fastest selection time for two-level menus over both movement conditions. Performing with the next best times, a pull down menu may be a suitable choice in the case where a pie menu is not appropriate as the interaction technique. Teamed with the touchpad, the pull down menu reported the second fastest time (after the trackball). The trackball teamed with the pull down menu enables the fastest selection time for single-level menus over both movement conditions. The linear fixed or pie pop-up menus could form a suitable choice in the case where a pull down menu is not appropriate as the interaction technique for single-level menus. Teamed with the touchpad, the linear fixed and pie pop-up single-level menus reported the second fastest times (after the trackball).

Table 51: Combined pointing device and user interface component summary. Green represents a first ranking, orange a second ranking and red represents a third ranking. The darker shading represents faster times and the lighter shading indicates slower times (left to right). Pp, Pd, Lf and Lp represent pie pop-up, pull down, linear fixed and linear pop-up menus respectively. Target sizes are 16, 32 and 48 pixels and distances are 300 and 500 pixels, i.e. 16x500 represents a target size of 16 pixels placed at 500 pixels apart

	Menu (two-level)				**Menu** (single-level)				**Selection** (learnability)					
Device	**Pp**	**Pd**	**Lf**	**Lp**	**Pd**	**Lf**	**Pp**	**Lp**	**48x300**	**32x300**	**48x500**	**32x500**	**16x300**	**16x500**
Trackball														
Touchpad														
Twiddler2														
Gyroscopic														

The combination of the trackball and the target size/distance combination of 48×300 pixels allows for the fastest selection time, as depicted in Table 51. Where a target size of 48 pixels is not appropriate, the target size of 32 pixels could form a suitable choice, performing with the next best time, and comparably with the target size of 48 pixels placed at 500 pixels apart. For target sizes of 32 pixels, positioned 300 pixels apart, the touchpad performs with the next best time (after the trackball).

8.5 Device Guidelines and Recommendations

The culmination of the usability studies and synthesis of results provide insights pertaining to the choice and usability of the devices in a wearable context as summarised

in this chapter and detailed in Chapters 3 - 6. The work also provides guidelines and insights that will be used to inform the design of future wearable input devices. The guidelines are derived from the quantitative and qualitative findings and from the lessons learned from the numerous evaluations undertaken as part of this dissertation. Although the guidelines are specific to the design of wearable pointing devices, where appropriate, they may be generalised to influence and guide the design of wearable input devices in the broad. The guidelines should be examined and appropriated in a way that suits the context and mode of use. Designers may need to weigh the costs and benefits of applying the guidelines and choose those that most meet the user's requirements and their context of use. In addition to influencing the design process, the guidelines and recommendations may also be used to guide users towards the selection of a suitable wearable input device; that is, the guidelines form a checklist that may be utilised as a point of comparison when choosing between the various input devices available.

8.6 Novel Pointing Device

The set of guidelines derived from the four usability studies were applied to design a pointing device with a novel form factor, suitable for use within a wearable context (i.e. while wearing a computer and for use with a head-worn display). As described in Section 7.3, the wearable pointing device was designed to be worn on the user's index finger and runs down the back of the user's hand. The device is positioned on the hand so as to allow the use of both hands to interact with the task/environment when the device is not in use. Thus, the device allows for short grasp/access time given that it is designed to be worn continuously attached to the hand. Cursor movement is via an optical mouse sensor and button press is via capacitive buttons. The device was created in order to be subtle and unobtrusive, and provide discrete, socially acceptable interaction with a wearable computer.

8.7 Future Work and Limitations

While this body of work provides valuable contributions to the area of wearable computing, it is not without its limitations. This section explores the limitations of the work while also suggesting possible avenues for future work. A limitation of the first target selection study is that the touchpad mouse was not evaluated against the other devices; however, this is

rectified by its inclusion in the learnability study (and other studies) that evaluates the devices performing target selection tasks (repeated exposure over time). Ideally, the same criterion to assess usability would have been used for all studies, for example, workload would have been a useful measure across all of the tasks, i.e. drag and drop and menu selection in order to determine whether and how task contributes to workload. Likewise, PPWS would be an interesting measure for the selection and drag and drop studies, also to determine whether the results are influenced by task as well as pointing device. Although the drag and drop study evaluated participants while walking, it did so using one target size and distance combination only; it would be interesting to discover whether a range of task difficulty (size and distance) values would produce similar results.

In the learnability extended evaluation, a decision was made not to evaluate the pointing device while mobile, given that the aim of the study was to evaluate the learnability of the devices. Future work could explore the effect of repeated exposure to the input devices while walking, in order to determine whether this would lend itself to participants being able to walk closer to their preferred walking speed. Similarly it would be interesting to evaluate the mobility of the devices over a longitudinal study to determine whether certain devices are easier to use while walking, allowing users to reach speeds closer to their preferred walking speeds more rapidly with certain devices over others. Results obtained from the performance of the Twiddler2 in the learnability extended study suggest that it may be interesting to evaluate the devices over more sessions in order to determine whether an increase in efficiency and effectiveness is evidenced, and to what capacity. Recently the Twiddler3[50] has been released with an improved ergonomic design and different pointing mechanism. Cursor movement is performed via an 8-way Nav Stick. Movement to the desired target requires a zig-zag motion of the Nav Stick which differs from a standard mouse. Pressing on the Nav Stick performs either a right or left mouse click (chosen by the user). The Twiddler3 also introduces three extra buttons on the front of the device (placed above the keyboard keys) that operate as left, middle and right mouse clicks. The Twiddler3 is a wireless device. Evaluation of the Twiddler3 would prove interesting given the improved form factor and pointing mechanism.

In addition to the studies presented, it would be valuable to evaluate the devices in a grasp and park test, in order to determine which of the devices perform most efficiently in this

[50] http://twiddler.tekgear.com/

regard; that is, which devices are able to be quickly held in the hand when needed and then holstered when not in use (in order to free the hands for other tasks), and quantify the devices accordingly. Although the results of this study may be unsurprising given the type of the pointing device and whether it is worn on the body, it would nonetheless be valuable to confirm this with a user study, as per Ashbrook et al. [65]. Another avenue for future work would involve evaluating the pointing device implemented as part of this body of work. In addition, it would be interesting to develop devices with different form factors but with the same interaction mechanism in order to determine the degree in which form factor influences usability measures such as performance. Reducing the current size of the pointing device implemented as part of this dissertation to resemble jewellery would be an interesting and valuable avenue of exploration.

In regards to the larger space of wearable interaction, many open questions and avenues for exploration remain. Over the course of this dissertation, it has become clear that wearable interaction remains an unsolved problem; one that is vital to wearable computing. To this end, an exploration into appropriate input modalities, interaction techniques and interaction metaphors that are appropriate and suitable for wearable head-worn displays would be valuable and necessary, particularly given the emergence of new head-worn displays. In addition, it would be beneficial to explore interaction techniques that fall outside the space of cursor-controlled interaction but are still executed via a small, unobtrusive input device of sorts (requiring subtle interaction), for example, as per Lucero et al. [2]. Although challenging, it would be valuable to explore the possibility of achieving the same level of functionality that cursor-controlled interaction provides, without the need to manipulate a cursor. For example, Tinmith-Hand [46] separates cursor-control from command entry via a menu system. The menu system maps commands to the user's fingers. The user activates a command by pinching the appropriate finger and thumb together.

While some researchers suggest cursor-controlled interaction is not suitable for wearable interaction, the following suggested studies would provide empirical evidence to confirm or refute their claims, in place of anecdotal evidence in this area. It would prove interesting to explore cursor-controlled interaction against other interaction techniques to ascertain how the two sit in the same space together, for example, in terms of performance, workload and other usability measures. Perhaps ways of making cursor-controlled interaction more

appropriate for wearable interaction should be explored, as per Hong et al. [217]. The comparison of cursor-controlled interaction with reading text on a head-worn display to ascertain the level of user attention, workload and other appropriate measures required for both activities would also be a valuable and interesting evaluation.

8.8 Concluding Remarks

Effective input devices and interaction techniques are essential to the usability of a wearable computing system. With the imminent release of wearable technology poised to hit mainstream markets, research into wearable input devices and interaction continues to be an important field of investigation. How one interacts with wearable devices is becoming increasingly important as such devices grow in popularity. Wearable head-worn displays are moving towards being smaller, less obtrusive and are targeting the consumer market. Within this wearable space, the necessity to understand appropriate input devices and interaction with head-worn displays is vital. Although this dissertation provides contributions to this important area, many questions and avenues for exploration remain. The pending introduction of new wearable technologies may change the landscape and bring with it new challenges or further highlight the existing ones as we seek to resolve the existing wearable interaction questions. Researchers have cast an exciting vision of wearable computing and have made significant and compelling advances in this regard, however, we have not yet achieved the 'ultimate wearable computer' [26]; appropriate, suitable, socially acceptable and effective interaction is one pillar underpinning this endeavour.

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A

Appendix A: Wearable Input Device Evaluation Studies (Summary)

Table 52: Limited Wearable Input Device Evaluation Studies - Summary

Publication	Task	Dependent measures	Display	Devices	Results and Comments	Wearable and Mobility	Longi-tudinal
Thomas et al. (1997) [218]	Text entry.	Time and errors per character	Private eye monocular display	1. Forearm mounted keyboard 2. Virtual keyboard (via belt mounted isometric joystick) 3. Kordic keypad.	The devices could be ranked as follows; forearm keyboard, virtual keyboard followed by the Kordic keypad. The forearm keyboard performed the fastest and more stably of the devices.	Yes. Pheonix 2 computer, headset and Private Eye display. Standing.	Six one hour sessions spread over a three week period.
Thomas et al. (1997, 2002) [151, 152]	Target selection	Task completion time and error rate	Sony Glasstron see-through 800x600 SVGA display	EasyCat Touchpad	The authors note that in the case where one mouse position is to be used for all for postures, the forearm position would be the best choice. Qualitative results indicate participants preferred the forearm placement.	Toshiba Portable Personal Computer 320 Series laptop computer placed in a backpack. Sitting, standing, kneeling and prone posture positions.	-
Rosenberg (1998) [138]	Target selection	Throughput	-	1. Biofeedback pointer (new device) 2. Mouse	Biofeedback Pointer performed 14% as well as the standard mouse.	-	-
Davis (2001) [216].	Target selection	-	-	Twiddler, Thumbelina mini trackball, optical mouse, wireless ball-driven mouse, full-size trackballs, touchpad, built-in pointing device of the Xybernaut MA-IV.	Empirical results not reported.	-	-
Lehikoinen and Röykkee (2003) [150]	Object selection – new	Time taken to select correct object	Laptop LCD screen (desktop) and	1. Mouse 2. Trackball	The 1D selection technique when compared to 2D	Walking condition: wearable	-

	interaction technique		Sony Glasstron PLM-S700E head-worn display (walking)		traditional selection was slower in both stationary and walking conditions.	computer with trackball. Desktop condition: laptop LCD screen with mouse.	
Wither and Höllerer (2004) [215]	3D cursor positioning techniques (interaction techniques).	Time and error	Sony Glasstron PLM-S700E head-worn display	T1 Twiddler2 keyboard, T2 RocketMouse finger trackball, T3 head orientation and two buttons, and T4 head orientation with a switch mode button	T2 and T3 techniques were faster than the T1 and T4 techniques. No significant differences between the T2 and T3, and T1 and T4 techniques. Users preferred the T2 technique.	-	-
Chamberlain and Kalawsky (2004) [10]	Target selection	Time to point, error rate (target misses) and workload	Vest-based Xybernaut MA IV fold down touch screen worn just above the hip	1. Stylus on touchscreen 2. Off-table mouse	Stylus was the fastest device (918.3 ms faster in the standing condition and 963.7 ms faster in the walking condition) and had the lowest cognitive workload. The mouse took 145.9 ms longer to use while walking and the stylus took 101 ms longer to use however, these findings are not statistically significant. The off-table mouse reported the lower error rate. The off-table mouse reported the lower error rate (the stylus resulting in 24.2 and 19.7 more errors in the standing and walking conditions respectively). Significantly higher overall workload for the off-table mouse. Physical, temporal, effort and performance all significantly different. Voice recognition ruled out - found to be	Yes. Participants donned a vest based wearable computer system (Xybernaut MA IV) with fold down touch screen. Standing and walking.	-

					problematic in pilot study.		
Lyons et al. (2004) [219]	Text entry	Words per minute and error rate	Computer monitor	1. Twiddler (Multi-tap method) 2. Twiddler (Chording method)	19.8 wpm for multi-tap and 26.2 wpm for chording by session 20. By the eighth session, participants typed faster chording than with the multi-tap. Chording typing rates did not level off, increasing steadily, while the multi-tap speeds began to plateau.	No. Sitting.	20 sessions.
Lyons et al. (2004) [220]	Text entry	Words per minute and error rate	Computer monitor	Twiddler	By session 40, participants achieved an average typing rate of 37.3 wpm. Results of the final study revealed that an average typing rate of 47 wpm was reached.	No. Sitting.	20 sessions with an additional 5 sessions to evaluate blind-typing and multi-character chords.
Chamberlain (2004 PhD Thesis) [214]	Target selection	Task time, error rate (target misses) and workload	Vest-based Xybernaut MA IV fold down touch screen worn just above the hip	1. Stylus 2 Trackpad 3. Off-table mouse	Between-subjects design (three groups of ten participants all on different input devices). Significant difference found between all three devices for total task time and error. Significant difference on workload except for the off-table mouse and trackpad. Time (standing): Stylus 545.246 (SD 18.72427), Trackpad 747.209 (SD 64.00642), Off-table 1463.552 (SD 102.4597) Error (standing): Off-table 35.5 (SD 14.69732), Stylus 59.5 (SD 15.58668), Trackpad 76.6 (SD 7.560129). Workload (standing): Stylus 24.1 (SD 8.9), Trackpad 46.8 (SD 13.9), Off-table 47.2 (SD 6.2) Time (walking): Stylus 646.698 (SD	Yes. Standing and walking.	No.

					33.36), Trackpad 1043.744 (SD 150.0511), Off-table 1619.732 (SD 84.254) Error (walking): Off-table 31.3 (SD 12.84134), Stylus 51 (SD 24.11546), Trackpad 80.8 (SD 8.638415). Workload (walking): Stylus 33.1 (SD 11.3), Off-table 49.5 (SD 9.2), Trackpad 65.4 (SD 13.2)		
Chamberlain (2004 PhD Thesis) [214]	Drag and drop	Task time, error rate (drop misses) and workload	Vest-based Xybernaut MA IV fold down touch screen worn just above the hip	1. Stylus 2 Trackpad 3. Off-table mouse	Significant difference found between stylus and off-table mouse only for total task time. Significant difference found between the stylus and off-table mouse, and stylus and trackpad for errors. Significant difference on workload for the stylus and off-table mouse and stylus and track-pad. Time (standing): Stylus 295.056 (SD 110.912), Trackpad 301.577 (SD 54.280), Off-table 340.959 (SD 53.748) Error (standing): Stylus 76.2 (SD 17.041), Off-table 295.8 (SD 74.118), Trackpad 251.9 (SD 84.856). Workload (standing): Stylus 28.4 (SD 18.00), Off-table 64.5 (SD 10.39), Trackpad 64.7 (SD 6.91) Time (walking): Stylus 508.844 (SD 108.068), Trackpad 688.639 (SD 111.441), Off-table 720.920 (SD	Yes. Standing and walking.	

					209.568) Error (walking): Stylus 96.3 (SD 18.625), Trackpad 298.9 (SD 63.320), Off-table 340.4 (SD 53.610). Workload (walking): Stylus 32.4 (SD 8.19), Trackpad 67.9 (SD 16.67), Off-table 68.6 (SD 15.24)		
Chamberlain (2004 PhD Thesis) [214]	Trajectory-based input	Task time, error rate and workload	Vest-based Xybernaut MA IV fold down touch screen worn just above the hip	1. Stylus 2 Trackpad 3. Off-table mouse	Significant differences between all of the devices for task time and errors. Significant difference between the stylus and off-table mouse and stylus and track-pad. Time (standing): Stylus 316.033 (SD 81.56315), Trackpad 523.344 (SD 284.5992), Off-table 867.336 (SD 328.5203) Error (standing): Stylus 94.90 (SD 34.35582), Trackpad 302.00 (SD 85.24084), Off-table 441.00 (SD 128.8091). Workload (standing): Stylus 30.5 (SD 9.395), Trackpad 63.6 (SD 9.155), Off-table 69.7 (SD 17.204) Time (walking): Stylus 571.541 (SD 119.9539), Trackpad 1165.986 (SD 125.9976), Off-table 1836.563 (SD 349.6757) Error (walking): Stylus 303.90 (SD 93.17063), Trackpad 388.20 (SD 103.8501),	Yes. Standing and walking.	

					Off-table 819.40 (SD 93.17063). Workload (walking): Stylus 44.6 (SD 12.020), Trackpad 66.6 (SD 11.177), Off-table 71.4 (SD 10.782)		
Clarkson et al. (2005) [221]	Text entry	Words per minute and error rate	Computer monitor	Two mini-QWERTY keyboards by Dell and Targus	Results indicated that the Targus which averaged typing speeds of 61.44 wpm was significantly faster than the Dell which averaged speeds of 58.61 wpm.	No. Desktop computer.	20 sessions over the course of 11 days.
Clawson et al. (2005) [222]	Text entry	Words per minute and error rate	Computer monitor	Two mini-QWERTY keyboards by Dell and Targus under normal, single blind and double blind conditions.	Participants reached rates of 45.8 wpm across the blind conditions and 57.04 wpm for the normal condition. Accuracy across the blind conditions was 85.6% while the normal condition was 93.6%.	No. Desktop computer.	Five sessions lasting 75 minutes each.
Hong et al. (2005) [217]	Target selection evaluating a new interaction technique	Movement time and throughput	Micro-optical head-worn display and 17" CRT	1. Dolphin mouse trackball 2. Generic mouse	Average Movement Time: Normal gain 2.104 sec, dynamic gain 1.918 sec (significantly different). Throughput (wearable condition): Dynamic gain 2.22 bps, normal gain 1.59 bps. Throughput (desktop condition): Normal gain 5.88 bps, dynamic gain improves 0.66 bps. Throughput is calculated using the reciprocal of the slope of the regression line.	Desktop condition sitting at a monitor using the mouse. Wearable condition with a head-worn display using the trackball.	-
Kim et al. (2005) [88]	Target selection		-	1. SCURRY (new device) 2. Gyration optical mouse	Devices were found to perform similarly (no significant difference was found).	-	-
Hwang et al. (2005) [140]	Target selection	Task time, error rate, and throughput	-	1. Feeltip (new device) 2. Spring-loaded joystick	1. 2.63 bps (SD 0.48) 2. 2.27 bps (SD 0.50) Not clear how throughput is calculated.	-	Target selection and text entry tasks spread over five days.

	1D menu selection	Task time	-		1. 5.7 secs 2. 6.5 secs	-	-
	2D map navigation	Task time	-		1. 5.5 secs 2. 7.6 secs	-	-
	Text entry	Words per minute	-		7.23 wpm in session 5 for Feeltip	-	-
Witt and Kluge (2008) [9]	Menu selection (4 to 7 menu items)	Task completion time	Monocular head-worn display (MicroOptical SV-6)	1. Trackball 2. Data glove (gesture recognition) 3. Speech recognition.	In short navigation tasks, laymen were significantly faster with the trackball hand mouse than with a data glove. Domain experts performed comparably across all three devices. In the long navigation tasks, laymen performed comparably well across all three devices and domain experts were significantly slower with speech. Users wore a vest that housed an OQO computer to simulate wearing a wearable computer. Head-worn display and devices are actually connected to a stationary computer running the experiment software.	Yes (see comments). Standing.	-
Ashbrook et al. (2008) [65]	Accessing and respondin g to alerts on a device placed on the wrist, in the pocket and holstered on the hip	Device access time	Motorola E680i camera phone with 320x240 colour touchscreen display	Motorola E680i phone	The wrist provided the fastest access time. It was found that placing the device in a pocket or holster incurs a large time penalty of up to 78% of access time.	Yes. Standing and walking.	-
Oakley et al. (2008) [5]	Target selection	Task completion time, error rate, and throughput	24 inch flat panel display	Inertial sensor pack; 1. Held in the hand 2. On the back of the hand 3. On the wrist	Held position performed better than the wrist. Hand positions just over 3 bps and wrist just under. Exact throughput values were not reported, throughput values ascertained from the	No. Standing (one meter away from display).	-

					graph. Calculated as per ISO 9241-9.		
Tokoro et al. (2009) [3]	Target selection	Elapsed time	PC monitor	1. Optical mouse 2. Trackball 3. Joystick 4. Wii remote controller 5. New method using accelerometers	Trackball, joystick and optical mouse performed better than the proposed accelerometer technique.	-	-
Bajer et al. (2012) [87]	Text entry	Words per minute, error rate(%), keystrokes per character	Laptop monitor	Huffman Base-4 Text Entry Glove (H4-TEG)	Participants reached text entry speeds of 14.0 wpm after 9 sessions of practice with mean error rates less than 1%.	No. Laptop computer.	Eleven sessions lasting one hour each.
Horie et al. (2012) [142]	Target selection	Elapsed time	Monocular head-worn display.	1. Body mounted accelerometers (i.e. index finger, elbow, shin, little finger, back of hand, foot, thumb and middle finger on one hand, wrist and head and hand) 2. Trackball 3. Wii remote	Trackball and Wii remote performed better than the accelerometer conditions. Results show a stabilizing of performance on the third or fourth day for all conditions except for the shin and wrist which took longer to stabilise and the trackball which stabilised following day one.	No. Computer not worn on body. Standing and sitting.	Tasks undertaken over seven days.
Calvo et al. (2012) [143]	Multi-directional tapping task as per ISO 9241-9	Movement time, distance for each trial, and throughput	MR-1 GD2000 with a 5.6" screen	1. G3 (new pointing device mounted into a tactical glove) 2. Touchpad 3. Ttrackpoint (embedded into MR-1 GD2000 chassis) 4. Mouse	G3 3.13 bps, SD 0.22 Touchpad 2.46 bps, SD 0.15 Trackpoint 1.49 bps, SD 0.07 Mouse 4.741 Throughput as per ISO 9241-9 and Soukoreff and MacKenzie recommendations. G3 was found to have significantly faster movement time, higher throughput, however performed with more errors than the other two devices.	Yes. MR-1 GD2000 on a tactical vest. Standing.	
Chen et al. (2013) [4]	Cursor control	Error (in pixels)	Monitor	uTrack	Participants were able to use uTrack for cursor control tasks.	Seated.	-

					Participants preferred the finger and stylus for cursor control.		
Chan et al. (2013) [6]	Target selection	Task time and error rate	13-inch display on a macbook air	FingerPad - two selection methods; flick and bimanual click method	No significant difference between walking and seated completion times. A significant difference of error rate between the walking and seated completion times when target size was below 2.5 mm was found. The flick gesture required for selecting targets performed significantly slower than the click method in the walking condition only.	Seated and walking (on a treadmill).	-
Kato and Yanagihara (2013) [1]	Target selection	Time and error	Head-worn display (Sony HMZ-T1)	1. Pacman UI 2. Wireless mouse	Pacman UI 1.560 secs, SD 0.978 Wireless mouse 2.778 secs, SD 1.159 Pacman UI performs 44% faster than the wireless mouse.	-	-

B

Appendix B: Participant Questionnaires

B.1 Selection Study Questionnaire

PARTICIPANT QUESTIONNAIRE FOR INPUT DEVICE SATISFACTION

Age:_____ Sex:_____

Number of years experience using computer:_____

Number of hours per week using window based computers:_____

Prior to this experiment, have you worn a Head Mounted Display? YES / NO

Prior to this experiment, have you used any of the following input devices:

If so, please circle the input device(s) you have used and specify the total number of hours spent using the device on the corresponding line above.

Trackball_____ Twiddler Mouse_____ Gyroscopic Mouse_____

PLEASE CIRCLE THE NUMBER WHICH BEST CORRESPONDS TO YOUR RATING.

1. Overall reaction to the Trackball input device. Describe your experience using the Trackball.

Ease of use	very easy	1	2	3	4	5	6	7	very difficult
Speed of use	too fast	1	2	3	4	5	6	7	too slow
Accuracy	very precise	1	2	3	4	5	6	7	very imprecise
Intuitive	very intuitive	1	2	3	4	5	6	7	very confusing
Comfort	very comfortable	1	2	3	4	5	6	7	very uncomfortable
Cursor Movement	very easy	1	2	3	4	5	6	7	very difficult
Button Press	very easy	1	2	3	4	5	6	7	very difficult

2. Overall reaction to the Gyroscopic Mouse input device. Describe your experience using the Gyroscopic Mouse.

Ease of use	very easy	1	2	3	4	5	6	7	very difficult
Speed of use	too fast	1	2	3	4	5	6	7	too slow
Accuracy	very precise	1	2	3	4	5	6	7	very imprecise
Intuitive	very intuitive	1	2	3	4	5	6	7	very confusing
Comfort	very comfortable	1	2	3	4	5	6	7	very uncomfortable
Cursor Movement	very easy	1	2	3	4	5	6	7	very difficult
Button Press	very easy	1	2	3	4	5	6	7	very difficult

3. Overall reaction to the Twiddler Mouse input device. Describe your experience using the Twiddler Mouse.

Ease of use	very easy	1	2	3	4	5	6	7	very difficult
Speed of use	too fast	1	2	3	4	5	6	7	too slow
Accuracy	very precise	1	2	3	4	5	6	7	very imprecise
Intuitive	very intuitive	1	2	3	4	5	6	7	very confusing
Comfort	very comfortable	1	2	3	4	5	6	7	very uncomfortable
Cursor Movement	very easy	1	2	3	4	5	6	7	very difficult
Button Press	very easy	1	2	3	4	5	6	7	very difficult

4. Rank the input devices according to ease of use.
(1 for easiest, 3 for hardest)

_____Trackball
_____Gyroscopic Mouse
_____Twiddler Mouse

Trackball Input Device

5. **Were there any aspects of the Trackball that made moving the cursor and/or pressing the button to select targets difficult? If so, please describe.**

6. **What did you like about using the Trackball?**

7. **What did you dislike about using the Trackball?**

Gyroscopic Mouse Input Device

8. **Were there any aspects of the Gyroscopic Mouse that made moving the cursor and/or pressing the button to select targets difficult? If so, please describe.**

9. **What did you like about using the Gyroscopic Mouse?**

10. **What did you dislike about using the Gyroscopic Mouse?**

Twiddler Mouse Input Device

11. Were there any aspects of the Twiddler Mouse that made moving the cursor and/or pressing the button to select targets difficult? If so, please describe.

_____

_____

_____

12. What did you like about using the Twiddler Mouse?

_____

_____

_____

13. What did you dislike about using the Twiddler Mouse?

_____

_____

_____

14. Did you experience any discomfort, pain or illness while wearing the computer, head mounted display and using the input devices? Please circle appropriate one.

Yes **No**

If you circled Yes, please indicate where you experienced the pain and the level of pain experienced. (If applicable, you may choose more than one).

Head	no pain	1	2	3	4	5	6	7	very painful
Eyes	no pain	1	2	3	4	5	6	7	very painful
Neck	no pain	1	2	3	4	5	6	7	very painful
Back	no pain	1	2	3	4	5	6	7	very painful
Hands	no pain	1	2	3	4	5	6	7	very painful
Arms	no pain	1	2	3	4	5	6	7	very painful

Other_____

Please provide as much information as you can regarding any discomfort, pain or illness you experienced.

_____

_____

_____

_____

15. Any other comments?

_____

_____

_____

Thank you for your time!

B.2 Drag and Drop Study Questionnaire – Standing and Walking

PARTICIPANT QUESTIONNAIRE FOR INPUT DEVICE SATISFACTION
SESSION TWO - STATIONARY EXPERIMENT

PLEASE CIRCLE THE NUMBER WHICH BEST CORRESPONDS TO YOUR RATING.

1. Overall reaction to the TRACKBALL input device while stationary. Describe your experience using the TRACKBALL.

Force required for actuation	very uncomfortable	1	2	3	4	5	6	7	very comfortable
Smoothness during operation	very rough	1	2	3	4	5	6	7	very smooth
Effort required for operation	very high	1	2	3	4	5	6	7	very low
Accuracy	very inaccurate	1	2	3	4	5	6	7	very accurate
Operation speed	unacceptable	1	2	3	4	5	6	7	acceptable
General comfort	very uncomfortable	1	2	3	4	5	6	7	very comfortable
Overall operation of device	very difficult (to use)	1	2	3	4	5	6	7	very easy (to use)
Finger fatigue	very high	1	2	3	4	5	6	7	none
Wrist fatigue	very high	1	2	3	4	5	6	7	none
Arm fatigue	very high	1	2	3	4	5	6	7	none
Shoulder fatigue	very high	1	2	3	4	5	6	7	none
Neck fatigue	very high	1	2	3	4	5	6	7	none
Ease of use	very difficult	1	2	3	4	5	6	7	very easy
Speed of use	too slow	1	2	3	4	5	6	7	too fast
Accuracy	very imprecise	1	2	3	4	5	6	7	very precise
Intuitive	very confusing	1	2	3	4	5	6	7	very intuitive
Comfort	very uncomfortable	1	2	3	4	5	6	7	very comfortable
Cursor Movement	very difficult	1	2	3	4	5	6	7	very easy
Button Press	very difficult	1	2	3	4	5	6	7	very easy
Dragging	very difficult	1	2	3	4	5	6	7	very easy

2. Overall reaction to the GYROSCOPIC MOUSE input device while stationary. Describe your experience using the GYROSCOPIC MOUSE.

Force required for actuation	very uncomfortable	1	2	3	4	5	6	7	very comfortable
Smoothness during operation	very rough	1	2	3	4	5	6	7	very smooth
Effort required for operation	very high	1	2	3	4	5	6	7	very low
Accuracy	very inaccurate	1	2	3	4	5	6	7	very accurate
Operation speed	unacceptable	1	2	3	4	5	6	7	acceptable
General comfort	very uncomfortable	1	2	3	4	5	6	7	very comfortable
Overall operation of device	very difficult (to use)	1	2	3	4	5	6	7	very easy (to use)
Finger fatigue	very high	1	2	3	4	5	6	7	none
Wrist fatigue	very high	1	2	3	4	5	6	7	none
Arm fatigue	very high	1	2	3	4	5	6	7	none
Shoulder fatigue	very high	1	2	3	4	5	6	7	none
Neck fatigue	very high	1	2	3	4	5	6	7	none
Ease of use	very difficult	1	2	3	4	5	6	7	very easy
Speed of use	too slow	1	2	3	4	5	6	7	too fast
Accuracy	very imprecise	1	2	3	4	5	6	7	very precise
Intuitive	very confusing	1	2	3	4	5	6	7	very intuitive
Comfort	very uncomfortable	1	2	3	4	5	6	7	very comfortable
Cursor Movement	very difficult	1	2	3	4	5	6	7	very easy
Button Press	very difficult	1	2	3	4	5	6	7	very easy
Dragging	very difficult	1	2	3	4	5	6	7	very easy

3. Overall reaction to the TWIDDLER MOUSE input device while stationary. Describe your experience using the TWIDDLER MOUSE.

Force required for actuation	very uncomfortable	1	2	3	4	5	6	7	very comfortable
Smoothness during operation	very rough	1	2	3	4	5	6	7	very smooth
Effort required for operation	very high	1	2	3	4	5	6	7	very low
Accuracy	very inaccurate	1	2	3	4	5	6	7	very accurate
Operation speed	unacceptable	1	2	3	4	5	6	7	acceptable
General comfort	very uncomfortable	1	2	3	4	5	6	7	very comfortable
Overall operation of device	very difficult (to use)	1	2	3	4	5	6	7	very easy (to use)
Finger fatigue	very high	1	2	3	4	5	6	7	none
Wrist fatigue	very high	1	2	3	4	5	6	7	none
Arm fatigue	very high	1	2	3	4	5	6	7	none
Shoulder fatigue	very high	1	2	3	4	5	6	7	none
Neck fatigue	very high	1	2	3	4	5	6	7	none
Ease of use	very difficult	1	2	3	4	5	6	7	very easy
Speed of use	too slow	1	2	3	4	5	6	7	too fast
Accuracy	very imprecise	1	2	3	4	5	6	7	very precise
Intuitive	very confusing	1	2	3	4	5	6	7	very intuitive
Comfort	very uncomfortable	1	2	3	4	5	6	7	very comfortable
Cursor Movement	very difficult	1	2	3	4	5	6	7	very easy
Button Press	very difficult	1	2	3	4	5	6	7	very easy
Dragging	very difficult	1	2	3	4	5	6	7	very easy

3. Overall reaction to the TOUCHPAD input device while stationary. Describe your experience using the TOUCHPAD.

Force required for actuation	very uncomfortable	1	2	3	4	5	6	7	very comfortable
Smoothness during operation	very rough	1	2	3	4	5	6	7	very smooth
Effort required for operation	very high	1	2	3	4	5	6	7	very low
Accuracy	very inaccurate	1	2	3	4	5	6	7	very accurate
Operation speed	unacceptable	1	2	3	4	5	6	7	acceptable
General comfort	very uncomfortable	1	2	3	4	5	6	7	very comfortable
Overall operation of device	very difficult (to use)	1	2	3	4	5	6	7	very easy (to use)
Finger fatigue	very high	1	2	3	4	5	6	7	none
Wrist fatigue	very high	1	2	3	4	5	6	7	none
Arm fatigue	very high	1	2	3	4	5	6	7	none
Shoulder fatigue	very high	1	2	3	4	5	6	7	none
Neck fatigue	very high	1	2	3	4	5	6	7	none
Ease of use	very difficult	1	2	3	4	5	6	7	very easy
Speed of use	too slow	1	2	3	4	5	6	7	too fast
Accuracy	very imprecise	1	2	3	4	5	6	7	very precise
Intuitive	very confusing	1	2	3	4	5	6	7	very intuitive
Comfort	very uncomfortable	1	2	3	4	5	6	7	very comfortable
Cursor Movement	very difficult	1	2	3	4	5	6	7	very easy
Button Press	very difficult	1	2	3	4	5	6	7	very easy
Dragging	very difficult	1	2	3	4	5	6	7	very easy

4. **Please Rank the input devices (Trackball, Gyroscopic Mouse, Twiddler Mouse & TouchPad) according to ease of use. (1 being easiest, 4 being hardest)**

   1. _____
   2. _____
   3. _____
   4. _____

TRACKBALL INPUT DEVICE

5. **Were there any aspects of the Trackball that made moving the cursor and/or pressing the button to drag and drop targets difficult? If so, please describe.**

_____
_____
_____

6. **What did you like about using the Trackball?**

_____
_____
_____

7. **What did you dislike about using the Trackball?**

_____
_____
_____

GYROSCOPIC MOUSE INPUT DEVICE

8. **Were there any aspects of the Gyroscopic Mouse that made moving the cursor and/or pressing the button to drag and drop targets difficult? If so, please describe.**

_____
_____
_____

9. **What did you like about using the Gyroscopic Mouse?**

_____
_____
_____

10. **What did you dislike about using the Gyroscopic Mouse?**

_____
_____
_____

TWIDDLER MOUSE INPUT DEVICE

Please circle the technique you used to select targets: A key E key D key

11. Were there any aspects of the Twiddler Mouse that made moving the cursor and/or pressing the button to drag and drop targets difficult? If so, please describe.

12. What did you like about using the Twiddler Mouse?

13. What did you dislike about using the Twiddler Mouse?

TOUCHPAD INPUT DEVICE

Please circle the technique you used to select targets: Left click Double tap

14. Were there any aspects of the TouchPad that made moving the cursor and/or pressing the button to drag and drop targets difficult? If so, please describe.

15. What did you like about using the TouchPad?

16. What did you dislike about using the TouchPad?

17. Did you experience any discomfort, pain or illness while wearing the computer, head mounted display and using the input devices? Please circle appropriate one.

Yes **No**

If you circled Yes, please indicate where you experienced the pain and the level of pain experienced. (If applicable, you may choose more than one).

Head	no pain	1	2	3	4	5	6	7	very painful
Eyes	no pain	1	2	3	4	5	6	7	very painful
Neck	no pain	1	2	3	4	5	6	7	very painful
Back	no pain	1	2	3	4	5	6	7	very painful
Hands	no pain	1	2	3	4	5	6	7	very painful
Arms	no pain	1	2	3	4	5	6	7	very painful

Other_____

Please provide as much information as you can regarding any discomfort, pain or illness you experienced.

_____

_____

_____

_____

18. Any other comments?

_____

_____

_____

_____

_____

_____

_____

_____

_____

THANK YOU FOR YOUR TIME!

PARTICIPANT QUESTIONNAIRE FOR INPUT DEVICE SATISFACTION
SESSION TWO - WALKING EXPERIMENT

PLEASE CIRCLE THE NUMBER WHICH BEST CORRESPONDS TO YOUR RATING.

1. Overall reaction to the TRACKBALL input device while walking. Describe your experience using the TRACKBALL.

Force required for actuation	very uncomfortable	1	2	3	4	5	6	7	very comfortable
Smoothness during operation	very rough	1	2	3	4	5	6	7	very smooth
Effort required for operation	very high	1	2	3	4	5	6	7	very low
Accuracy	very inaccurate	1	2	3	4	5	6	7	very accurate
Operation speed	unacceptable	1	2	3	4	5	6	7	acceptable
General comfort	very uncomfortable	1	2	3	4	5	6	7	very comfortable
Overall operation of device	very difficult (to use)	1	2	3	4	5	6	7	very easy (to use)
Finger fatigue	very high	1	2	3	4	5	6	7	none
Wrist fatigue	very high	1	2	3	4	5	6	7	none
Arm fatigue	very high	1	2	3	4	5	6	7	none
Shoulder fatigue	very high	1	2	3	4	5	6	7	none
Neck fatigue	very high	1	2	3	4	5	6	7	none
Ease of use	very difficult	1	2	3	4	5	6	7	very easy
Speed of use	too slow	1	2	3	4	5	6	7	too fast
Accuracy	very imprecise	1	2	3	4	5	6	7	very precise
Intuitive	very confusing	1	2	3	4	5	6	7	very intuitive
Comfort	very uncomfortable	1	2	3	4	5	6	7	very comfortable
Cursor Movement	very difficult	1	2	3	4	5	6	7	very easy
Button Press	very difficult	1	2	3	4	5	6	7	very easy
Dragging	very difficult	1	2	3	4	5	6	7	very easy

2. Overall reaction to the GYROSCOPIC MOUSE input device while walking. Describe your experience using the GYROSCOPIC MOUSE.

Force required for actuation	very uncomfortable	1	2	3	4	5	6	7	very comfortable
Smoothness during operation	very rough	1	2	3	4	5	6	7	very smooth
Effort required for operation	very high	1	2	3	4	5	6	7	very low
Accuracy	very inaccurate	1	2	3	4	5	6	7	very accurate
Operation speed	unacceptable	1	2	3	4	5	6	7	acceptable
General comfort	very uncomfortable	1	2	3	4	5	6	7	very comfortable
Overall operation of device	very difficult (to use)	1	2	3	4	5	6	7	very easy (to use)
Finger fatigue	very high	1	2	3	4	5	6	7	none
Wrist fatigue	very high	1	2	3	4	5	6	7	none
Arm fatigue	very high	1	2	3	4	5	6	7	none
Shoulder fatigue	very high	1	2	3	4	5	6	7	none
Neck fatigue	very high	1	2	3	4	5	6	7	none
Ease of use	very difficult	1	2	3	4	5	6	7	very easy
Speed of use	too slow	1	2	3	4	5	6	7	too fast
Accuracy	very imprecise	1	2	3	4	5	6	7	very precise
Intuitive	very confusing	1	2	3	4	5	6	7	very intuitive
Comfort	very uncomfortable	1	2	3	4	5	6	7	very comfortable
Cursor Movement	very difficult	1	2	3	4	5	6	7	very easy
Button Press	very difficult	1	2	3	4	5	6	7	very easy
Dragging	very difficult	1	2	3	4	5	6	7	very easy

3. Overall reaction to the TWIDDLER MOUSE input device while walking. Describe your experience using the TWIDDLER MOUSE.

Force required for actuation	very uncomfortable	1	2	3	4	5	6	7	very comfortable
Smoothness during operation	very rough	1	2	3	4	5	6	7	very smooth
Effort required for operation	very high	1	2	3	4	5	6	7	very low
Accuracy	very inaccurate	1	2	3	4	5	6	7	very accurate
Operation speed	unacceptable	1	2	3	4	5	6	7	acceptable
General comfort	very uncomfortable	1	2	3	4	5	6	7	very comfortable
Overall operation of device	very difficult (to use)	1	2	3	4	5	6	7	very easy (to use)
Finger fatigue	very high	1	2	3	4	5	6	7	none
Wrist fatigue	very high	1	2	3	4	5	6	7	none
Arm fatigue	very high	1	2	3	4	5	6	7	none
Shoulder fatigue	very high	1	2	3	4	5	6	7	none
Neck fatigue	very high	1	2	3	4	5	6	7	none
Ease of use	very difficult	1	2	3	4	5	6	7	very easy
Speed of use	too slow	1	2	3	4	5	6	7	too fast
Accuracy	very imprecise	1	2	3	4	5	6	7	very precise
Intuitive	very confusing	1	2	3	4	5	6	7	very intuitive
Comfort	very uncomfortable	1	2	3	4	5	6	7	very comfortable
Cursor Movement	very difficult	1	2	3	4	5	6	7	very easy
Button Press	very difficult	1	2	3	4	5	6	7	very easy
Dragging	very difficult	1	2	3	4	5	6	7	very easy

3. Overall reaction to the TOUCHPAD input device while walking. Describe your experience using the TOUCHPAD.

Force required for actuation	very uncomfortable	1	2	3	4	5	6	7	very comfortable
Smoothness during operation	very rough	1	2	3	4	5	6	7	very smooth
Effort required for operation	very high	1	2	3	4	5	6	7	very low
Accuracy	very inaccurate	1	2	3	4	5	6	7	very accurate
Operation speed	unacceptable	1	2	3	4	5	6	7	acceptable
General comfort	very uncomfortable	1	2	3	4	5	6	7	very comfortable
Overall operation of device	very difficult (to use)	1	2	3	4	5	6	7	very easy (to use)
Finger fatigue	very high	1	2	3	4	5	6	7	none
Wrist fatigue	very high	1	2	3	4	5	6	7	none
Arm fatigue	very high	1	2	3	4	5	6	7	none
Shoulder fatigue	very high	1	2	3	4	5	6	7	none
Neck fatigue	very high	1	2	3	4	5	6	7	none
Ease of use	very difficult	1	2	3	4	5	6	7	very easy
Speed of use	too slow	1	2	3	4	5	6	7	too fast
Accuracy	very imprecise	1	2	3	4	5	6	7	very precise
Intuitive	very confusing	1	2	3	4	5	6	7	very intuitive
Comfort	very uncomfortable	1	2	3	4	5	6	7	very comfortable
Cursor Movement	very difficult	1	2	3	4	5	6	7	very easy
Button Press	very difficult	1	2	3	4	5	6	7	very easy
Dragging	very difficult	1	2	3	4	5	6	7	very easy

4. **Please Rank the input devices (Trackball, Gyroscopic Mouse, Twiddler Mouse & TouchPad) according to ease of use. (1 being easiest, 4 being hardest)**

   1. _____
   2. _____
   3. _____
   4. _____

TRACKBALL INPUT DEVICE

5. **Were there any aspects of the Trackball that made moving the cursor and/or pressing the button to drag and drop targets difficult? If so, please describe.**

_____
_____
_____

6. **What did you like about using the Trackball?**

_____
_____
_____

7. **What did you dislike about using the Trackball?**

_____
_____
_____

GYROSCOPIC MOUSE INPUT DEVICE

8. **Were there any aspects of the Gyroscopic Mouse that made moving the cursor and/or pressing the button to drag and drop targets difficult? If so, please describe.**

_____
_____
_____

9. **What did you like about using the Gyroscopic Mouse?**

_____
_____
_____

10. **What did you dislike about using the Gyroscopic Mouse?**

_____
_____
_____

TWIDDLER MOUSE INPUT DEVICE

Please circle the technique you used to select targets: A key E key D key

11. Were there any aspects of the Twiddler Mouse that made moving the cursor and/or pressing the button to drag and drop targets difficult? If so, please describe.

12. What did you like about using the Twiddler Mouse?

13. What did you dislike about using the Twiddler Mouse?

TOUCHPAD INPUT DEVICE

Please circle the technique you used to select targets: Left click Double tap

14. Were there any aspects of the TouchPad that made moving the cursor and/or pressing the button to drag and drop targets difficult? If so, please describe.

15. What did you like about using the TouchPad?

16. What did you dislike about using the TouchPad?

17. Did you experience any discomfort, pain or illness while wearing the computer, head mounted display and using the input devices? Please circle appropriate one.

Yes No

If you circled Yes, please indicate where you experienced the pain and the level of pain experienced. (If applicable, you may choose more than one).

Head	no pain	1	2	3	4	5	6	7	very painful
Eyes	no pain	1	2	3	4	5	6	7	very painful
Neck	no pain	1	2	3	4	5	6	7	very painful
Back	no pain	1	2	3	4	5	6	7	very painful
Hands	no pain	1	2	3	4	5	6	7	very painful
Arms	no pain	1	2	3	4	5	6	7	very painful

Other_____

Please provide as much information as you can regarding any discomfort, pain or illness you experienced.

_____

_____

_____

_____

18. Any other comments?

_____

_____

_____

_____

_____

_____

_____

_____

_____

THANK YOU FOR YOUR TIME!

B.3 Menu Selection Study Questionnaire

PARTICIPANT QUESTIONNAIRE FOR INPUT DEVICE SATISFACTION

SESSION TWO – STATIONARY TASKS

TRACKBALL



Overall reaction to the TRACKBALL input device while stationary. Describe your experience using the TRACKBALL.
PLEASE CIRCLE THE NUMBER WHICH BEST CORRESPONDS TO YOUR RATING.

Force required for actuation	very uncomfortable	1	2	3	4	5	6	7	very comfortable
Smoothness during operation	very rough	1	2	3	4	5	6	7	very smooth
Effort required for operation	very high	1	2	3	4	5	6	7	very low
Accuracy	very inaccurate	1	2	3	4	5	6	7	very accurate
Operation speed	unacceptable	1	2	3	4	5	6	7	acceptable
Cursor Movement	very difficult	1	2	3	4	5	6	7	very easy
Button Press	very difficult	1	2	3	4	5	6	7	very easy
Menu selection	very difficult	1	2	3	4	5	6	7	very easy
Intuitive	very confusing	1	2	3	4	5	6	7	very intuitive
General comfort	very uncomfortable	1	2	3	4	5	6	7	very comfortable
Overall operation of device	very difficult (to use)	1	2	3	4	5	6	7	very easy (to use)
Finger effort	very high	1	2	3	4	5	6	7	None
Wrist effort	very high	1	2	3	4	5	6	7	none
Arm effort	very high	1	2	3	4	5	6	7	none
Shoulder effort	very high	1	2	3	4	5	6	7	none
Neck effort	very high	1	2	3	4	5	6	7	none
Finger fatigue	very high	1	2	3	4	5	6	7	none
Wrist fatigue	very high	1	2	3	4	5	6	7	none
Arm fatigue	very high	1	2	3	4	5	6	7	none
Shoulder fatigue	very high	1	2	3	4	5	6	7	none
Neck fatigue	very high	1	2	3	4	5	6	7	none

PARTICIPANT QUESTIONNAIRE FOR INPUT DEVICE SATISFACTION

SESSION TWO – STATIONARY TASKS

GYROSCOPIC MOUSE



Overall reaction to the GYROSCOPIC MOUSE input device while stationary. Describe your experience using the GYROSCOPIC MOUSE.
PLEASE CIRCLE THE NUMBER WHICH BEST CORRESPONDS TO YOUR RATING.

Force required for actuation	very uncomfortable	1	2	3	4	5	6	7	very comfortable
Smoothness during operation	very rough	1	2	3	4	5	6	7	very smooth
Effort required for operation	very high	1	2	3	4	5	6	7	very low
Accuracy	very inaccurate	1	2	3	4	5	6	7	very accurate
Operation speed	unacceptable	1	2	3	4	5	6	7	acceptable
Cursor Movement	very difficult	1	2	3	4	5	6	7	very easy
Button Press	very difficult	1	2	3	4	5	6	7	very easy
Menu selection	very difficult	1	2	3	4	5	6	7	very easy
Intuitive	very confusing	1	2	3	4	5	6	7	very intuitive
General comfort	very uncomfortable	1	2	3	4	5	6	7	very comfortable
Overall operation of device	very difficult (to use)	1	2	3	4	5	6	7	very easy (to use)
Finger effort	very high	1	2	3	4	5	6	7	None
Wrist effort	very high	1	2	3	4	5	6	7	none
Arm effort	very high	1	2	3	4	5	6	7	none
Shoulder effort	very high	1	2	3	4	5	6	7	none
Neck effort	very high	1	2	3	4	5	6	7	none
Finger fatigue	very high	1	2	3	4	5	6	7	none
Wrist fatigue	very high	1	2	3	4	5	6	7	none
Arm fatigue	very high	1	2	3	4	5	6	7	none
Shoulder fatigue	very high	1	2	3	4	5	6	7	none
Neck fatigue	very high	1	2	3	4	5	6	7	none

PARTICIPANT QUESTIONNAIRE FOR INPUT DEVICE SATISFACTION

SESSION TWO – STATIONARY TASKS

TWIDDLER (TRACKPOINT) MOUSE



Overall reaction to the TWIDDLER MOUSE input device while stationary. Describe your experience using the TWIDDLER MOUSE.
PLEASE CIRCLE THE NUMBER WHICH BEST CORRESPONDS TO YOUR RATING.

Force required for actuation	very uncomfortable	1	2	3	4	5	6	7	very comfortable
Smoothness during operation	very rough	1	2	3	4	5	6	7	very smooth
Effort required for operation	very high	1	2	3	4	5	6	7	very low
Accuracy	very inaccurate	1	2	3	4	5	6	7	very accurate
Operation speed	unacceptable	1	2	3	4	5	6	7	acceptable
Cursor Movement	very difficult	1	2	3	4	5	6	7	very easy
Button Press	very difficult	1	2	3	4	5	6	7	very easy
Menu selection	very difficult	1	2	3	4	5	6	7	very easy
Intuitive	very confusing	1	2	3	4	5	6	7	very intuitive
General comfort	very uncomfortable	1	2	3	4	5	6	7	very comfortable
Overall operation of device	very difficult (to use)	1	2	3	4	5	6	7	very easy (to use)
Finger effort	very high	1	2	3	4	5	6	7	None
Wrist effort	very high	1	2	3	4	5	6	7	none
Arm effort	very high	1	2	3	4	5	6	7	none
Shoulder effort	very high	1	2	3	4	5	6	7	none
Neck effort	very high	1	2	3	4	5	6	7	none
Finger fatigue	very high	1	2	3	4	5	6	7	none
Wrist fatigue	very high	1	2	3	4	5	6	7	none
Arm fatigue	very high	1	2	3	4	5	6	7	none
Shoulder fatigue	very high	1	2	3	4	5	6	7	none
Neck fatigue	very high	1	2	3	4	5	6	7	none

PARTICIPANT QUESTIONNAIRE FOR INPUT DEVICE SATISFACTION

SESSION TWO – STATIONARY TASKS

TOUCHPAD



Overall reaction to the TOUCHPAD input device while stationary. Describe your experience using the TOUCHPAD.
PLEASE CIRCLE THE NUMBER WHICH BEST CORRESPONDS TO YOUR RATING.

Force required for actuation	very uncomfortable	1	2	3	4	5	6	7	very comfortable
Smoothness during operation	very rough	1	2	3	4	5	6	7	very smooth
Effort required for operation	very high	1	2	3	4	5	6	7	very low
Accuracy	very inaccurate	1	2	3	4	5	6	7	very accurate
Operation speed	unacceptable	1	2	3	4	5	6	7	acceptable
Cursor Movement	very difficult	1	2	3	4	5	6	7	very easy
Button Press	very difficult	1	2	3	4	5	6	7	very easy
Menu selection	very difficult	1	2	3	4	5	6	7	very easy
Intuitive	very confusing	1	2	3	4	5	6	7	very intuitive
General comfort	very uncomfortable	1	2	3	4	5	6	7	very comfortable
Overall operation of device	very difficult (to use)	1	2	3	4	5	6	7	very easy (to use)
Finger effort	very high	1	2	3	4	5	6	7	None
Wrist effort	very high	1	2	3	4	5	6	7	none
Arm effort	very high	1	2	3	4	5	6	7	none
Shoulder effort	very high	1	2	3	4	5	6	7	none
Neck effort	very high	1	2	3	4	5	6	7	none
Finger fatigue	very high	1	2	3	4	5	6	7	none
Wrist fatigue	very high	1	2	3	4	5	6	7	none
Arm fatigue	very high	1	2	3	4	5	6	7	none
Shoulder fatigue	very high	1	2	3	4	5	6	7	none
Neck fatigue	very high	1	2	3	4	5	6	7	none

PARTICIPANT QUESTIONNAIRE FOR INPUT DEVICE SATISFACTION

SESSION TWO – WALKING TASKS

TRACKBALL



Overall reaction to the TRACKBALL input device while walking. Describe your experience using the TRACKBALL.
PLEASE CIRCLE THE NUMBER WHICH BEST CORRESPONDS TO YOUR RATING.

Force required for actuation	very uncomfortable	1	2	3	4	5	6	7	very comfortable
Smoothness during operation	very rough	1	2	3	4	5	6	7	very smooth
Effort required for operation	very high	1	2	3	4	5	6	7	very low
Accuracy	very inaccurate	1	2	3	4	5	6	7	very accurate
Operation speed	unacceptable	1	2	3	4	5	6	7	acceptable
Cursor Movement	very difficult	1	2	3	4	5	6	7	very easy
Button Press	very difficult	1	2	3	4	5	6	7	very easy
Menu selection	very difficult	1	2	3	4	5	6	7	very easy
Intuitive	very confusing	1	2	3	4	5	6	7	very intuitive
General comfort	very uncomfortable	1	2	3	4	5	6	7	very comfortable
Overall operation of device	very difficult (to use)	1	2	3	4	5	6	7	very easy (to use)
Finger effort	very high	1	2	3	4	5	6	7	None
Wrist effort	very high	1	2	3	4	5	6	7	none
Arm effort	very high	1	2	3	4	5	6	7	none
Shoulder effort	very high	1	2	3	4	5	6	7	none
Neck effort	very high	1	2	3	4	5	6	7	none
Finger fatigue	very high	1	2	3	4	5	6	7	none
Wrist fatigue	very high	1	2	3	4	5	6	7	none
Arm fatigue	very high	1	2	3	4	5	6	7	none
Shoulder fatigue	very high	1	2	3	4	5	6	7	none
Neck fatigue	very high	1	2	3	4	5	6	7	none

PARTICIPANT QUESTIONNAIRE FOR INPUT DEVICE SATISFACTION

SESSION TWO – WALKING TASKS

GYROSCOPIC MOUSE



Overall reaction to the GYROSCOPIC MOUSE input device while walking. Describe your experience using the GYROSCOPIC MOUSE.
PLEASE CIRCLE THE NUMBER WHICH BEST CORRESPONDS TO YOUR RATING.

Force required for actuation	very uncomfortable	1	2	3	4	5	6	7	very comfortable
Smoothness during operation	very rough	1	2	3	4	5	6	7	very smooth
Effort required for operation	very high	1	2	3	4	5	6	7	very low
Accuracy	very inaccurate	1	2	3	4	5	6	7	very accurate
Operation speed	unacceptable	1	2	3	4	5	6	7	acceptable
Cursor Movement	very difficult	1	2	3	4	5	6	7	very easy
Button Press	very difficult	1	2	3	4	5	6	7	very easy
Menu selection	very difficult	1	2	3	4	5	6	7	very easy
Intuitive	very confusing	1	2	3	4	5	6	7	very intuitive
General comfort	very uncomfortable	1	2	3	4	5	6	7	very comfortable
Overall operation of device	very difficult (to use)	1	2	3	4	5	6	7	very easy (to use)
Finger effort	very high	1	2	3	4	5	6	7	None
Wrist effort	very high	1	2	3	4	5	6	7	none
Arm effort	very high	1	2	3	4	5	6	7	none
Shoulder effort	very high	1	2	3	4	5	6	7	none
Neck effort	very high	1	2	3	4	5	6	7	none
Finger fatigue	very high	1	2	3	4	5	6	7	none
Wrist fatigue	very high	1	2	3	4	5	6	7	none
Arm fatigue	very high	1	2	3	4	5	6	7	none
Shoulder fatigue	very high	1	2	3	4	5	6	7	none
Neck fatigue	very high	1	2	3	4	5	6	7	none

PARTICIPANT QUESTIONNAIRE FOR INPUT DEVICE SATISFACTION

SESSION TWO – WALKING TASKS

TWIDDLER (TRACKPOINT) MOUSE



Overall reaction to the TWIDDLER MOUSE input device while walking. Describe your experience using the TWIDDLER MOUSE.
PLEASE CIRCLE THE NUMBER WHICH BEST CORRESPONDS TO YOUR RATING.

Force required for actuation	very uncomfortable	1	2	3	4	5	6	7	very comfortable
Smoothness during operation	very rough	1	2	3	4	5	6	7	very smooth
Effort required for operation	very high	1	2	3	4	5	6	7	very low
Accuracy	very inaccurate	1	2	3	4	5	6	7	very accurate
Operation speed	unacceptable	1	2	3	4	5	6	7	acceptable
Cursor Movement	very difficult	1	2	3	4	5	6	7	very easy
Button Press	very difficult	1	2	3	4	5	6	7	very easy
Menu selection	very difficult	1	2	3	4	5	6	7	very easy
Intuitive	very confusing	1	2	3	4	5	6	7	very intuitive
General comfort	very uncomfortable	1	2	3	4	5	6	7	very comfortable
Overall operation of device	very difficult (to use)	1	2	3	4	5	6	7	very easy (to use)
Finger effort	very high	1	2	3	4	5	6	7	None
Wrist effort	very high	1	2	3	4	5	6	7	none
Arm effort	very high	1	2	3	4	5	6	7	none
Shoulder effort	very high	1	2	3	4	5	6	7	none
Neck effort	very high	1	2	3	4	5	6	7	none
Finger fatigue	very high	1	2	3	4	5	6	7	none
Wrist fatigue	very high	1	2	3	4	5	6	7	none
Arm fatigue	very high	1	2	3	4	5	6	7	none
Shoulder fatigue	very high	1	2	3	4	5	6	7	none
Neck fatigue	very high	1	2	3	4	5	6	7	none

PARTICIPANT QUESTIONNAIRE FOR INPUT DEVICE SATISFACTION

SESSION TWO – WALKING TASKS

TOUCHPAD



Overall reaction to the TOUCHPAD input device while walking. Describe your experience using the TOUCHPAD.
PLEASE CIRCLE THE NUMBER WHICH BEST CORRESPONDS TO YOUR RATING.

Force required for actuation	very uncomfortable	1	2	3	4	5	6	7	very comfortable
Smoothness during operation	very rough	1	2	3	4	5	6	7	very smooth
Effort required for operation	very high	1	2	3	4	5	6	7	very low
Accuracy	very inaccurate	1	2	3	4	5	6	7	very accurate
Operation speed	unacceptable	1	2	3	4	5	6	7	acceptable
Cursor Movement	very difficult	1	2	3	4	5	6	7	very easy
Button Press	very difficult	1	2	3	4	5	6	7	very easy
Menu selection	very difficult	1	2	3	4	5	6	7	very easy
Intuitive	very confusing	1	2	3	4	5	6	7	very intuitive
General comfort	very uncomfortable	1	2	3	4	5	6	7	very comfortable
Overall operation of device	very difficult (to use)	1	2	3	4	5	6	7	very easy (to use)
Finger effort	very high	1	2	3	4	5	6	7	None
Wrist effort	very high	1	2	3	4	5	6	7	none
Arm effort	very high	1	2	3	4	5	6	7	none
Shoulder effort	very high	1	2	3	4	5	6	7	none
Neck effort	very high	1	2	3	4	5	6	7	none
Finger fatigue	very high	1	2	3	4	5	6	7	none
Wrist fatigue	very high	1	2	3	4	5	6	7	none
Arm fatigue	very high	1	2	3	4	5	6	7	none
Shoulder fatigue	very high	1	2	3	4	5	6	7	none
Neck fatigue	very high	1	2	3	4	5	6	7	none

PARTICIPANT QUESTIONNAIRE FOR INPUT DEVICE SATISFACTION
SESSION TWO – GENERAL

INPUT DEVICES:

TRACKBALL



GYROSCOPIC MOUSE



TWIDDLER2 MOUSE



TOUCHPAD



Please rank the input devices listed above according to ease of use while stationary. (1 being easiest, 4 being hardest).

1. _____
2. _____
3. _____
4. _____

Please rank the input devices listed above according to ease of use while walking. (1 being easiest, 4 being hardest).

1. _____
2. _____
3. _____
4. _____

Given the option to choose among the above input devices to be used with a wearable computer, which would be your preferred choice?

1. _____

I would prefer to use a wearable input device that is attached to the body (i.e. forearm, upper arm, finger, front of thigh, side of thigh, etc. True / False

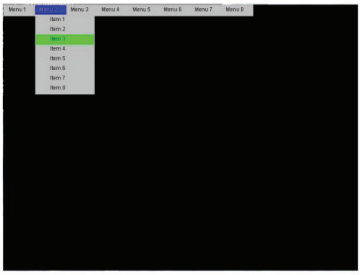
Preferred position for attaching wearable input device to the body:_____
_____

Given the option to choose among the above input devices to be attached to you if possible, which would be your preferred choice?_____

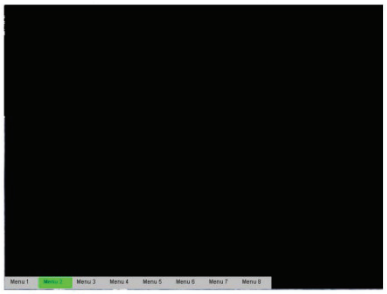
I would prefer to use a wearable input device that is held in the hand. True / False

MENU STRUCTURES:

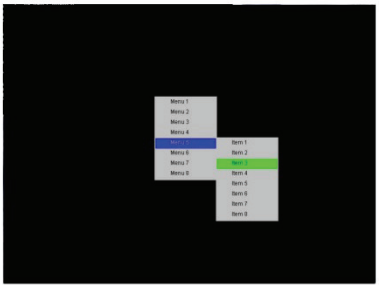
PULL DOWN (FIXED AT TOP)



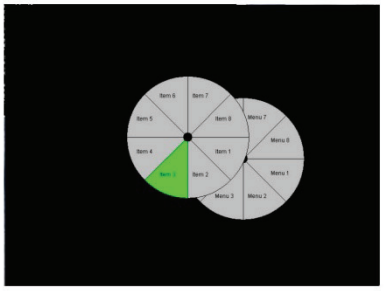
LINEAR (FIXED AT BOTTOM)



LINEAR POP UP



PIE POP UP



Please rank the menu structures listed above according to ease of use while stationary. (1 being easiest, 4 being hardest).

1. _____
2. _____
3. _____
4. _____

Please rank the menu structures listed above according to ease of use while walking. (1 being easiest, 4 being hardest).

1. _____
2. _____
3. _____
4. _____

Given the option to choose among the above menu structures to be used with a wearable computer, which would be your preferred choice?

1. _____

TRACKBALL INPUT DEVICE



Were there any aspects of the Trackball that made moving the cursor and/or pressing the button to select menu items difficult? If so, please describe.

_____
_____
_____
_____

What did you like about using the Trackball?

_____
_____
_____
_____

What did you dislike about using the Trackball?

_____
_____
_____
_____

Do you have any suggestions how to improve this device?

_____
_____
_____
_____

Was there a menu structure that you preferred to use with the Trackball? If so, please name the menu structure and briefly explain why.

_____
_____
_____
_____

GYROSCOPIC MOUSE INPUT DEVICE



Were there any aspects of the Gyroscopic Mouse that made moving the cursor and/or pressing the button to select menu items difficult? If so, please describe.

_____
_____
_____
_____

What did you like about using the Gyroscopic Mouse?

_____
_____
_____
_____

What did you dislike about using the Gyroscopic Mouse?

_____
_____
_____
_____

Do you have any suggestions how to improve this device?

_____
_____
_____
_____

Was there a menu structure that you preferred to use with the Gyroscopic Mouse? If so, please name the menu structure and briefly explain why.

_____
_____
_____
_____

TWIDDLER MOUSE (TRACKPOINT) INPUT DEVICE



Please circle the technique you used to select menu items: A key E key

Were there any aspects of the Twiddler Mouse that made moving the cursor and/or pressing the button to select menu items difficult? If so, please describe.

_____
_____
_____
_____

What did you like about using the Twiddler Mouse?

_____
_____
_____
_____

What did you dislike about using the Twiddler Mouse?

_____
_____
_____
_____

Do you have any suggestions how to improve this device?

_____
_____
_____
_____

Was there a menu structure that you preferred to use with the Twiddler Mouse? If so, please name the menu structure and briefly explain why.

_____
_____
_____
_____

TOUCHPAD INPUT DEVICE



Please circle the technique you used to select menu items: Left click Single tap

Were there any aspects of the TouchPad that made moving the cursor and/or pressing the button to select menu items difficult? If so, please describe.

What did you like about using the TouchPad?

What did you dislike about using the TouchPad?

Do you have any suggestions how to improve this device?

Was there a menu structure that you preferred to use with the TouchPad? If so, please name the menu structure and briefly explain why.

Did you experience any discomfort, pain or illness while wearing the computer, head mounted display and using the input devices? Please circle appropriate one.

Yes **No**

If you circled Yes, please indicate where you experienced the pain and the level of pain experienced. (If applicable, you may choose more than one).

Head	no pain	1	2	3	4	5	6	7	very painful
Eyes	no pain	1	2	3	4	5	6	7	very painful
Neck	no pain	1	2	3	4	5	6	7	very painful
Back	no pain	1	2	3	4	5	6	7	very painful
Hands	no pain	1	2	3	4	5	6	7	very painful
Arms	no pain	1	2	3	4	5	6	7	very painful

Other_____

Please provide as much information as you can regarding any discomfort, pain or illness you experienced.

_____

_____

_____

_____

Any other comments?

_____

_____

_____

_____

_____

_____

_____

_____

_____

THANK YOU FOR YOUR TIME!

B.4 Learnability Study Questionnaire

PARTICIPANT QUESTIONNAIRE FOR INPUT DEVICE SATISFACTION

SESSIONS ONE – SIX

TRACKBALL



Overall reaction to the TRACKBALL input device. Describe your experience using the TRACKBALL. PLEASE CIRCLE THE NUMBER WHICH BEST CORRESPONDS TO YOUR RATING.

Force required for actuation	very uncomfortable	1	2	3	4	5	6	7	very comfortable
Smoothness during operation	very rough	1	2	3	4	5	6	7	very smooth
Effort required for operation	very high	1	2	3	4	5	6	7	very low
Accuracy	very inaccurate	1	2	3	4	5	6	7	very accurate
Operation speed	unacceptable	1	2	3	4	5	6	7	acceptable
Cursor Movement	very difficult	1	2	3	4	5	6	7	very easy
Button Press	very difficult	1	2	3	4	5	6	7	very easy
Target selection	very difficult	1	2	3	4	5	6	7	very easy
Intuitive	very confusing	1	2	3	4	5	6	7	very intuitive
General comfort	very uncomfortable	1	2	3	4	5	6	7	very comfortable
Overall operation of device	very difficult (to use)	1	2	3	4	5	6	7	very easy (to use)
Finger effort	very high	1	2	3	4	5	6	7	None
Wrist effort	very high	1	2	3	4	5	6	7	none
Arm effort	very high	1	2	3	4	5	6	7	none
Shoulder effort	very high	1	2	3	4	5	6	7	none
Neck effort	very high	1	2	3	4	5	6	7	none
Finger fatigue	very high	1	2	3	4	5	6	7	none
Wrist fatigue	very high	1	2	3	4	5	6	7	none
Arm fatigue	very high	1	2	3	4	5	6	7	none
Shoulder fatigue	very high	1	2	3	4	5	6	7	none
Neck fatigue	very high	1	2	3	4	5	6	7	none

Workload rating

Workload rating while using the TRACKBALL input device.
PLEASE PLACE A MARK ON EACH SCALE THAT REPRESENTS THE MAGNITUDE OF EACH FACTOR IN THE TASK YOU JUST PERFORMED.

Mental Demand Low  High

How much mental and perceptual activity was required (e.g. thinking, deciding, calculating, remembering, looking, searching, etc.)? Was the task easy or demanding, simple or complex, exacting or forgiving?

Physical Demand Low  High

How much physical activity was required (e.g. pushing, pulling, turning, controlling, activating, etc.)? Was the task easy or demanding, slow or brisk, slack or strenuous, restful or laborious?

Temporal Demand Low  High

How much pressure did you feel due to the rate or pace at which the tasks or task elements occurred? Was the pace slow and leisurely or rapid and frantic?

Performance Good  Poor

How successful do you think you were in accomplishing the goals of the task set by the experimenter (or yourself)? How satisfied were you with your performance in accomplishing these goals?

Effort Low  High

How hard did you have to work (mentally and physically) to accomplish your level of performance?

Frustration level Low  High

How insecure, discouraged, irritated, stressed and annoyed versus secure, gratified, content, relaxed and complacent did you feel during the task?

NASA-TLX
Task Demand Comparisons

For each of the following, please place a mark to select the member of each pair that contributed more to the workload of the task. That is, what was more important to your experience of workload (was more demanding for you) in the task that you just performed.

Mental demand:	How mentally demanding was the task?
Physical demand:	How physically demanding was the task?
Temporal demand:	How hurried or rushed was the pace of the task?
Performance:	How successful were you in accomplishing what you were asked to do?
Effort:	How hard did you have to work to accomplish your level of performance?
Frustration:	How insecure, discouraged, irritated, stressed, and annoyed were you?

Trackball

01. _____	Physical Demand	OR	_____Mental Demand
02. _____	Temporal Demand	OR	_____Mental Demand
03. _____	Performance	OR	_____Mental Demand
04. _____	Frustration level	OR	_____Mental Demand
05. _____	Effort	OR	_____Mental Demand
06. _____	Temporal Demand	OR	_____Physical Demand
07. _____	Performance	OR	_____Physical Demand
08. _____	Frustration level	OR	_____Physical Demand
09. _____	Effort	OR	_____Physical Demand
10. _____	Temporal Demand	OR	_____Performance
11. _____	Temporal Demand	OR	_____Frustration level
12. _____	Temporal Demand	OR	_____Effort
13. _____	Performance	OR	_____Frustration level
14. _____	Performance	OR	_____Effort
15. _____	Effort	OR	_____Frustration level

PARTICIPANT QUESTIONNAIRE FOR INPUT DEVICE SATISFACTION

SESSIONS ONE – SIX

GYROSCOPIC MOUSE



Overall reaction to the GYROSCOPIC MOUSE input device. Describe your experience using the GYROSCOPIC MOUSE.
PLEASE CIRCLE THE NUMBER WHICH BEST CORRESPONDS TO YOUR RATING.

Force required for actuation	very uncomfortable	1	2	3	4	5	6	7	very comfortable
Smoothness during operation	very rough	1	2	3	4	5	6	7	very smooth
Effort required for operation	very high	1	2	3	4	5	6	7	very low
Accuracy	very inaccurate	1	2	3	4	5	6	7	very accurate
Operation speed	unacceptable	1	2	3	4	5	6	7	acceptable
Cursor Movement	very difficult	1	2	3	4	5	6	7	very easy
Button Press	very difficult	1	2	3	4	5	6	7	very easy
Target selection	very difficult	1	2	3	4	5	6	7	very easy
Intuitive	very confusing	1	2	3	4	5	6	7	very intuitive
General comfort	very uncomfortable	1	2	3	4	5	6	7	very comfortable
Overall operation of device	very difficult (to use)	1	2	3	4	5	6	7	very easy (to use)
Finger effort	very high	1	2	3	4	5	6	7	None
Wrist effort	very high	1	2	3	4	5	6	7	none
Arm effort	very high	1	2	3	4	5	6	7	none
Shoulder effort	very high	1	2	3	4	5	6	7	none
Neck effort	very high	1	2	3	4	5	6	7	none
Finger fatigue	very high	1	2	3	4	5	6	7	none
Wrist fatigue	very high	1	2	3	4	5	6	7	none
Arm fatigue	very high	1	2	3	4	5	6	7	none
Shoulder fatigue	very high	1	2	3	4	5	6	7	none
Neck fatigue	very high	1	2	3	4	5	6	7	none

Workload rating

Workload rating while using the GYROSCOPIC MOUSE input device.
PLEASE PLACE A MARK ON EACH SCALE THAT REPRESENTS THE MAGNITUDE OF EACH FACTOR IN THE TASK YOU JUST PERFORMED.

Mental Demand Low  High

How much mental and perceptual activity was required (e.g. thinking, deciding, calculating, remembering, looking, searching, etc.)? Was the task easy or demanding, simple or complex, exacting or forgiving?

Physical Demand Low  High

How much physical activity was required (e.g. pushing, pulling, turning, controlling, activating, etc.)? Was the task easy or demanding, slow or brisk, slack or strenuous, restful or laborious?

Temporal Demand Low  High

How much pressure did you feel due to the rate or pace at which the tasks or task elements occurred? Was the pace slow and leisurely or rapid and frantic?

Performance Good  Poor

How successful do you think you were in accomplishing the goals of the task set by the experimenter (or yourself)? How satisfied were you with your performance in accomplishing these goals?

Effort Low  High

How hard did you have to work (mentally and physically) to accomplish your level of performance?

Frustration level Low  High

How insecure, discouraged, irritated, stressed and annoyed versus secure, gratified, content, relaxed and complacent did you feel during the task?

NASA-TLX
Task Demand Comparisons

For each of the following, please place a mark to select the member of each pair that contributed more to the workload of the task. That is, what was more important to your experience of workload (was more demanding for you) in the task that you just performed.

Mental demand:	How mentally demanding was the task?
Physical demand:	How physically demanding was the task?
Temporal demand:	How hurried or rushed was the pace of the task?
Performance:	How successful were you in accomplishing what you were asked to do?
Effort:	How hard did you have to work to accomplish your level of performance?
Frustration:	How insecure, discouraged, irritated, stressed, and annoyed were you?

Gyroscopic Mouse

01. _____ Physical Demand OR _____Mental Demand

02. _____ Temporal Demand OR _____Mental Demand

03. _____ Performance OR _____Mental Demand

04. _____ Frustration level OR _____Mental Demand

05. _____ Effort OR _____Mental Demand

06. _____ Temporal Demand OR _____Physical Demand

07. _____ Performance OR _____Physical Demand

08. _____ Frustration level OR _____Physical Demand

09. _____ Effort OR _____Physical Demand

10. _____ Temporal Demand OR _____Performance

11. _____ Temporal Demand OR _____Frustration level

12. _____ Temporal Demand OR _____Effort

13. _____ Performance OR _____Frustration level

14. _____ Performance OR _____Effort

15. _____ Effort OR _____Frustration level

PARTICIPANT QUESTIONNAIRE FOR INPUT DEVICE SATISFACTION

SESSIONS ONE – SIX

TWIDDLER (TRACKPOINT) MOUSE



Overall reaction to the TWIDDLER MOUSE input device. Describe your experience using the TWIDDLER MOUSE.
PLEASE CIRCLE THE NUMBER WHICH BEST CORRESPONDS TO YOUR RATING.

Force required for actuation	very uncomfortable	1	2	3	4	5	6	7	very comfortable
Smoothness during operation	very rough	1	2	3	4	5	6	7	very smooth
Effort required for operation	very high	1	2	3	4	5	6	7	very low
Accuracy	very inaccurate	1	2	3	4	5	6	7	very accurate
Operation speed	unacceptable	1	2	3	4	5	6	7	acceptable
Cursor Movement	very difficult	1	2	3	4	5	6	7	very easy
Button Press	very difficult	1	2	3	4	5	6	7	very easy
Target selection	very difficult	1	2	3	4	5	6	7	very easy
Intuitive	very confusing	1	2	3	4	5	6	7	very intuitive
General comfort	very uncomfortable	1	2	3	4	5	6	7	very comfortable
Overall operation of device	very difficult (to use)	1	2	3	4	5	6	7	very easy (to use)
Finger effort	very high	1	2	3	4	5	6	7	None
Wrist effort	very high	1	2	3	4	5	6	7	none
Arm effort	very high	1	2	3	4	5	6	7	none
Shoulder effort	very high	1	2	3	4	5	6	7	none
Neck effort	very high	1	2	3	4	5	6	7	none
Finger fatigue	very high	1	2	3	4	5	6	7	none
Wrist fatigue	very high	1	2	3	4	5	6	7	none
Arm fatigue	very high	1	2	3	4	5	6	7	none
Shoulder fatigue	very high	1	2	3	4	5	6	7	none
Neck fatigue	very high	1	2	3	4	5	6	7	none

Workload rating

Workload rating while using the TWIDDLER MOUSE input device.
PLEASE PLACE A MARK ON EACH SCALE THAT REPRESENTS THE MAGNITUDE OF EACH FACTOR IN THE TASK YOU JUST PERFORMED.

Mental Demand Low  High

How much mental and perceptual activity was required (e.g. thinking, deciding, calculating, remembering, looking, searching, etc.)? Was the task easy or demanding, simple or complex, exacting or forgiving?

Physical Demand Low  High

How much physical activity was required (e.g. pushing, pulling, turning, controlling, activating, etc.)? Was the task easy or demanding, slow or brisk, slack or strenuous, restful or laborious?

Temporal Demand Low  High

How much pressure did you feel due to the rate or pace at which the tasks or task elements occurred? Was the pace slow and leisurely or rapid and frantic?

Performance Good  Poor

How successful do you think you were in accomplishing the goals of the task set by the experimenter (or yourself)? How satisfied were you with your performance in accomplishing these goals?

Effort Low  High

How hard did you have to work (mentally and physically) to accomplish your level of performance?

Frustration level Low  High

How insecure, discouraged, irritated, stressed and annoyed versus secure, gratified, content, relaxed and complacent did you feel during the task?

NASA-TLX
Task Demand Comparisons

For each of the following, please place a mark to select the member of each pair that contributed more to the workload of the task. That is, what was more important to your experience of workload (was more demanding for you) in the task that you just performed.

Mental demand:	How mentally demanding was the task?
Physical demand:	How physically demanding was the task?
Temporal demand:	How hurried or rushed was the pace of the task?
Performance:	How successful were you in accomplishing what you were asked to do?
Effort:	How hard did you have to work to accomplish your level of performance?
Frustration:	How insecure, discouraged, irritated, stressed, and annoyed were you?

Twiddler (Trackpoint) Mouse

01. _____ Physical Demand OR _____Mental Demand

02. _____ Temporal Demand OR _____Mental Demand

03. _____ Performance OR _____Mental Demand

04. _____ Frustration level OR _____Mental Demand

05. _____ Effort OR _____Mental Demand

06. _____ Temporal Demand OR _____Physical Demand

07. _____ Performance OR _____Physical Demand

08. _____ Frustration level OR _____Physical Demand

09. _____ Effort OR _____Physical Demand

10. _____ Temporal Demand OR _____Performance

11. _____ Temporal Demand OR _____Frustration level

12. _____ Temporal Demand OR _____Effort

13. _____ Performance OR _____Frustration level

14. _____ Performance OR _____Effort

15. _____ Effort OR _____Frustration level

PARTICIPANT QUESTIONNAIRE FOR INPUT DEVICE SATISFACTION

SESSIONS ONE – SIX

TOUCHPAD



Overall reaction to the TOUCHPAD input device. Describe your experience using the TOUCHPAD.
PLEASE CIRCLE THE NUMBER WHICH BEST CORRESPONDS TO YOUR RATING.

Force required for actuation	very uncomfortable	1	2	3	4	5	6	7	very comfortable
Smoothness during operation	very rough	1	2	3	4	5	6	7	very smooth
Effort required for operation	very high	1	2	3	4	5	6	7	very low
Accuracy	very inaccurate	1	2	3	4	5	6	7	very accurate
Operation speed	unacceptable	1	2	3	4	5	6	7	acceptable
Cursor Movement	very difficult	1	2	3	4	5	6	7	very easy
Button Press	very difficult	1	2	3	4	5	6	7	very easy
Target selection	very difficult	1	2	3	4	5	6	7	very easy
Intuitive	very confusing	1	2	3	4	5	6	7	very intuitive
General comfort	very uncomfortable	1	2	3	4	5	6	7	very comfortable
Overall operation of device	very difficult (to use)	1	2	3	4	5	6	7	very easy (to use)
Finger effort	very high	1	2	3	4	5	6	7	None
Wrist effort	very high	1	2	3	4	5	6	7	none
Arm effort	very high	1	2	3	4	5	6	7	none
Shoulder effort	very high	1	2	3	4	5	6	7	none
Neck effort	very high	1	2	3	4	5	6	7	none
Finger fatigue	very high	1	2	3	4	5	6	7	none
Wrist fatigue	very high	1	2	3	4	5	6	7	none
Arm fatigue	very high	1	2	3	4	5	6	7	none
Shoulder fatigue	very high	1	2	3	4	5	6	7	none
Neck fatigue	very high	1	2	3	4	5	6	7	none

Workload rating

Workload rating while using the TOUCHPAD input device.
PLEASE PLACE A MARK ON EACH SCALE THAT REPRESENTS THE MAGNITUDE OF EACH FACTOR IN THE TASK YOU JUST PERFORMED.

Mental Demand Low  High

How much mental and perceptual activity was required (e.g. thinking, deciding, calculating, remembering, looking, searching, etc.)? Was the task easy or demanding, simple or complex, exacting or forgiving?

Physical Demand Low  High

How much physical activity was required (e.g. pushing, pulling, turning, controlling, activating, etc.)? Was the task easy or demanding, slow or brisk, slack or strenuous, restful or laborious?

Temporal Demand Low  High

How much pressure did you feel due to the rate or pace at which the tasks or task elements occurred? Was the pace slow and leisurely or rapid and frantic?

Performance Good  Poor

How successful do you think you were in accomplishing the goals of the task set by the experimenter (or yourself)? How satisfied were you with your performance in accomplishing these goals?

Effort Low  High

How hard did you have to work (mentally and physically) to accomplish your level of performance?

Frustration level Low  High

How insecure, discouraged, irritated, stressed and annoyed versus secure, gratified, content, relaxed and complacent did you feel during the task?

NASA-TLX
Task Demand Comparisons

For each of the following, please place a mark to select the member of each pair that contributed more to the workload of the task. That is, what was more important to your experience of workload (was more demanding for you) in the task that you just performed.

Mental demand:	How mentally demanding was the task?
Physical demand:	How physically demanding was the task?
Temporal demand:	How hurried or rushed was the pace of the task?
Performance:	How successful were you in accomplishing what you were asked to do?
Effort:	How hard did you have to work to accomplish your level of performance?
Frustration:	How insecure, discouraged, irritated, stressed, and annoyed were you?

TouchPad

01. _____	Physical Demand	OR	_____Mental Demand
02. _____	Temporal Demand	OR	_____Mental Demand
03. _____	Performance	OR	_____Mental Demand
04. _____	Frustration level	OR	_____Mental Demand
05. _____	Effort	OR	_____Mental Demand
06. _____	Temporal Demand	OR	_____Physical Demand
07. _____	Performance	OR	_____Physical Demand
08. _____	Frustration level	OR	_____Physical Demand
09. _____	Effort	OR	_____Physical Demand
10. _____	Temporal Demand	OR	_____Performance
11. _____	Temporal Demand	OR	_____Frustration level
12. _____	Temporal Demand	OR	_____Effort
13. _____	Performance	OR	_____Frustration level
14. _____	Performance	OR	_____Effort
15. _____	Effort	OR	_____Frustration level

Workload rating

Workload rating while using the MOUSE input device.
PLEASE PLACE A MARK ON EACH SCALE THAT REPRESENTS THE MAGNITUDE OF EACH FACTOR IN THE TASK YOU JUST PERFORMED.

Mental Demand Low  High

How much mental and perceptual activity was required (e.g. thinking, deciding, calculating, remembering, looking, searching, etc.)? Was the task easy or demanding, simple or complex, exacting or forgiving?

Physical Demand Low  High

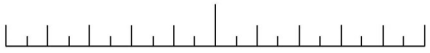
How much physical activity was required (e.g. pushing, pulling, turning, controlling, activating, etc.)? Was the task easy or demanding, slow or brisk, slack or strenuous, restful or laborious?

Temporal Demand Low  High

How much pressure did you feel due to the rate or pace at which the tasks or task elements occurred? Was the pace slow and leisurely or rapid and frantic?

Performance Good  Poor

How successful do you think you were in accomplishing the goals of the task set by the experimenter (or yourself)? How satisfied were you with your performance in accomplishing these goals?

Effort Low  High

How hard did you have to work (mentally and physically) to accomplish your level of performance?

Frustration level Low  High

How insecure, discouraged, irritated, stressed and annoyed versus secure, gratified, content, relaxed and complacent did you feel during the task?

NASA-TLX
Task Demand Comparisons

For each of the following, please place a mark to select the member of each pair that contributed more to the workload of the task. That is, what was more important to your experience of workload (was more demanding for you) in the task that you just performed.

Mental demand:	How mentally demanding was the task?
Physical demand:	How physically demanding was the task?
Temporal demand:	How hurried or rushed was the pace of the task?
Performance:	How successful were you in accomplishing what you were asked to do?
Effort:	How hard did you have to work to accomplish your level of performance?
Frustration:	How insecure, discouraged, irritated, stressed, and annoyed were you?

Desktop Mouse

01. _____ Physical Demand OR _____Mental Demand

02. _____ Temporal Demand OR _____Mental Demand

03. _____ Performance OR _____Mental Demand

04. _____ Frustration level OR _____Mental Demand

05. _____ Effort OR _____Mental Demand

06. _____ Temporal Demand OR _____Physical Demand

07. _____ Performance OR _____Physical Demand

08. _____ Frustration level OR _____Physical Demand

09. _____ Effort OR _____Physical Demand

10. _____ Temporal Demand OR _____Performance

11. _____ Temporal Demand OR _____Frustration level

12. _____ Temporal Demand OR _____Effort

13. _____ Performance OR _____Frustration level

14. _____ Performance OR _____Effort

15. _____ Effort OR _____Frustration level

PARTICIPANT QUESTIONNAIRE FOR INPUT DEVICE SATISFACTION
SESSIONS ONE – SIX: GENERAL

INPUT DEVICES:

TRACKBALL



GYROSCOPIC MOUSE



TWIDDLER2 MOUSE



TOUCHPAD



Please rank the input devices listed above according to ease of use.
(1 being easiest, 4 being hardest).

1. _____
2. _____
3. _____
4. _____

Given the option to choose among the above input devices to be used with a wearable computer, which would be your preferred choice?

1. _____

INPUT DEVICES:

TRACKBALL **GYROSCOPIC MOUSE** **TWIDDLER2 MOUSE** **TOUCHPAD**









Please rank the input devices listed above according to ease of learning (i.e. which device was the easiest to learn, which device was the most difficult to learn). (1 being easiest, 4 being hardest).

1. _____

2. _____

3. _____

4. _____

Which device do you feel you were more consistent with?

1. _____

Which device do you feel you improved with the most?

1. _____

TRACKBALL INPUT DEVICE

Were there any aspects of the Trackball that made moving the cursor and/or pressing the button to select targets difficult? If so, please describe.

_____

_____

_____

What did you like about using the Trackball?

_____

_____

_____

What did you dislike about using the Trackball?

_____

_____

_____

GYROSCOPIC MOUSE INPUT DEVICE

Were there any aspects of the Gyroscopic Mouse that made moving the cursor and/or pressing the button to select targets difficult? If so, please describe.

_____

_____

_____

What did you like about using the Gyroscopic Mouse?

_____

_____

_____

What did you dislike about using the Gyroscopic Mouse?

_____

_____

_____

TWIDDLER MOUSE (TRACKPOINT) INPUT DEVICE

Please circle the technique you used to select menu items: A key E key

Were there any aspects of the Twiddler Mouse that made moving the cursor and/or pressing the button to select targets difficult? If so, please describe.

_____

_____

_____

What did you like about using the Twiddler Mouse?

_____

_____

_____

What did you dislike about using the Twiddler Mouse?

_____

_____

_____

TOUCHPAD INPUT DEVICE

Please circle the technique you used to select targets: Left click Single tap

Were there any aspects of the TouchPad that made moving the cursor and/or pressing the button to select targets difficult? If so, please describe.

_____

_____

_____

What did you like about using the TouchPad?

_____

_____

_____

What did you dislike about using the TouchPad?

_____

_____

_____

Did you experience any discomfort, pain or illness while wearing the computer, head mounted display and using the input devices? Please circle appropriate one.

Yes **No**

If you circled Yes, please indicate where you experienced the pain and the level of pain experienced. (If applicable, you may choose more than one).

Head	no pain	1	2	3	4	5	6	7	very painful
Eyes	no pain	1	2	3	4	5	6	7	very painful
Neck	no pain	1	2	3	4	5	6	7	very painful
Back	no pain	1	2	3	4	5	6	7	very painful
Hands	no pain	1	2	3	4	5	6	7	very painful
Arms	no pain	1	2	3	4	5	6	7	very painful

Other_____

Please provide as much information as you can regarding any discomfort, pain or illness you experienced.

_____

_____

_____

_____

Any other comments?

_____

_____

_____

_____

_____

_____

_____

_____

_____

THANK YOU FOR YOUR TIME!

C

Appendix C: Qualitative Responses (Summary)

Trackball Qualitative Responses – Advantages / Like

Usage - General

- Ease of use
    - Easy to use x 12
    - Easy to use x 5 (walk)
        - Operates as well when moving (walk)
        - Same as standing still (walk)
    - I found the trackball to be one of the most easiest to handle.
    - It's simplicity for both movement and selection.
    - Easy to learn.
    - Easy to use, simple, just like using a normal mouse.
    - Easy plus too smooth to operate.
    - It is easy to use the trackball, the operation speed is very good.
    - Nothing more difficult than while stationary.
    - I loved it!
    - Most fun to use.
- Speed of use
    - Fast to move
    - Fast (walk)
    - Quick x 3
    - Speed x 4
        - Good speed
    - Speed (walk)
    - Speed and ability to quickly change from speed to accuracy
    - I could complete the operations speedily. It was not too sensitive.
    - Responsive
    - Very responsive, small movements move cursor easily.
    - Was a lot quicker by end of session 5 - learned improvement.
    - Very fast and easy.
    - The performance is very good, the speed of long distance tap.
    - Fast coarse movement.
    - Quick to move large distances.
    - Quick between targets.
- Effort required for operation
    - Little movement of wrist, arm.
    - Not much effort required.
    - Minimal effort required and the most accurate of all the devices.
- Smoothness during operation
    - Smooth to use - 1 handed.
    - Smooth (walk).
    - Smooth operation - relatively easy to make small corrections to pointer position.
    - Felt smoother / more accurate this week.
- Intuitive and familiar
    - Usage similar to a normal mouse and therefore very intuitive, fast to move, relaxing usage – the hand could even hang down.
    - Intuitive x 4
    - Intuitive (walk)
    - Similar to mouse. x 6
    - Similar to gaming console
    - Using my thumb to manipulate the ball was very intuitive - kind of like using a game console controller
    - Simple

    - Simple to use x 2 (walk)
        - Minimal concentration
    - Easy to learn how to use.
    - Mentally easy to pick up and understand.
    - Intuitive, simple to learn.
- Not affected by movement/walking x 2 (walk)
    - Smooth. Pointer stays in place while walking, turning etc. Not affected by walking motion.
    - Stable input device (walk)
    - When walking I had the most control of the cursor with this device - it wasn't affected by my movement
    - Could keep arm against torso to steady movement. (walk)
- Single handed use
    - One hand free (walk).
    - Hand operation even more: you'd probably be able to do other things whilst it's on your finger. (walk)
    - Could use it with just one hand, quick, easy accurate when moving. (walk)
    - Single hand use.

Cursor Movement and Button Press

- Cursor movement
    - Easy control of the cursor. (walk)
    - Easier to move cursor.
    - Easy to correct the movement.
    - Don't need to do too much movement except thumb.
    - Fast to move from previous target.
    - Easy navigation.
    - Ease of using the trackball to move cursor.
    - Easy to move, consistent movements, moves at a good pace.
    - No cursor movement when not used.
    - The ball was natural to use.
    - Easy/good control x 2
    - More control than the other input devices.
    - Good control, controllable speed. (walk)
    - Could control it easily (walk)
    - Reasonably steady
    - Fairly steady (walk)
    - Good to operate and select target with ball.
    - You always had a direct mechanical feedback loop created by your thumb on the ball which allowed for strict control over the cursor.
- Button press
    - Trigger button made selection very easy.
    - Easy to select, trigger button.
    - Button press in trigger position is easy and intuitive.
    - Easy trigger style click button.
    - Button pressing was easy and short movements also.
- Movement type
    - Easy to make directly horizontal or directly vertical movements.
    - You can use the inertia of the ball to move large distances quickly.
    - The function of the ball made the cursor easy to drag.
    - Using trackball is easy to make big movement but it is also easy to miss the target.
    - It is easy to make big movement when there is a long distance between two subjects.

- Accurate, precise and sensitive to use
    - Accurate x 12
    - Accurate x 4 (walk)
    - Can be really accurate as well as fast.
    - Extremely precise.
    - Precise.
    - Trackball seems to be the most comfortable and accurate combination.

Fatigue and pain

- No arm fatigue.
- Could drop device to side when arms became tired.
- Little fatigue and strain.

Form Factor

- Design, comfort and fit.
    - Nice and simple. Comfortable.
    - Comfortable to hold and to click.
    - Simple design, easy to hold and use.
    - It feels comfortable to hold.
    - Fits well into the hand.
    - Hand operation.
    - The holding position.
    - It fit snugly into my hand, without straining my thumb or fingers.
    - Comfortable to hold/use x 3
    - Comfortable to hold/use x 3 (walk)
    - Button separate from cursor movement.
    - Could drop device to side.
    - More natural to what I am used to.
    - Easier to hold than others.
    - I was comfortable using it.
    - Trackball was the most comfortable.
    - Being able to have hand anywhere and just use the thumb to move.
    - Can be used in any arm position.
    - Can hold arm against body to stabilise.
    - Sat well in my hand.
    - Easy to hold; intuitive.
    - Easy to hold.
    - Easy to pick up.
    - Nice form factor; convenient click button.
    - Ergonomic device, fit well in hand.
- Button
    - Easy trigger style click button.
    - The trigger button is easy and comfortable to use.
    - Placement of the press button.
    - Hard button.
    - The trigger button was also easy to use and well positioned.
    - Clicking with finger more like using traditional mouse.
    - The click button comfortable.
    - Buttons all work fine.
    - Select button.
    - Trigger style button.
- Size
    - Compact, non-intrusive.

    - Small x 8
    - Its size is good.
    - Easy compact device to use whilst walking. (walk).
    - The size was great if say this type of tech was used in public then it would be easy to pull out without it feeling like you are pulling out a large amount of wires and hardware.
- Weight
    - Light-weight x 11

Trackball Qualitative Responses – Disadvantages / Dislike

Usage - General

- Ease of use
    - Hand / eye coordination became inaccurate and a little difficult to use in comparison to stationary experiment. (walk)
    - Took a while to get adjusted to trackball after week off.
- Stability of device in hand
    - Very unstable as it is not fixed in a position for ease of use of the ball.
    - I had to hold it steady with my left hand which was a bit uncomfortable.
    - It moved around when trying to use it.
    - Moving cursor was difficult to get used to because it's not very stable.
    - Very unstable as it is not fixed in a position for ease of use of the ball.
    - Trackball device is not stable enough for precise control if held only one-handed.
    - I would like it more if it had a support. i.e. If it is fixed to something.
    - For better accuracy I felt I had to hold/operate with both hands.
    - Need to be held in two hands - then is ok
    - Needed left hand to support right hand whilst using it.
- Undesired ball movement
    - More than expected free movement of the ball.
    - Ball moves during walking when not desired sometime (walk).
    - Sometimes I tilted it wrong, the ball would automatically move certain directions.
    - If I held the trackball strangely the cursor would move by itself. (walk)
    - Had to be held still.
- Using the thumb
    - Thumb not usually used for precise work, not easy to use.
    - Thumb has to get used to the movement.
    - Thumb not usually used for precise work.
- The limitation of its functionality. i.e. requires input etc.
- Nothing
    - Nothing x 5 (walk).
    - Nothing x 3.

Cursor Movement and Button Press

- Cursor movement
    - Using my thumb alone made it difficult to move the cursor.
    - Cursor movement wasn’t smooth.
    - Slightly jumpy.
    - The ball would occasionally 'roll' without using the cursor this would occur at high speed.
    - The trackball would 'roll' when moved too quickly - the ball would roll, but not the cursor. (walk)
    - Walking would slightly wobble the finger and ball making cursor movement jerky. (walk)
    - The trackball can be moved fast so it's easy to lose the cursor.
    - Movement was very jittery; found I used second hand to stabilise the device.
    - Easy to accidentally nudge the sphere causing jittery movement and incorrect clicks.
    - Accidentally moving the cursor when lifting thumb off ball.
    - Too easy for the mouse pointer to get off track.
    - Very erratic.
    - Trackball had learning curve to remove the jitter.
- Button press

    - Due to size and position of hole for finger placement, only one finger is 'holding' this device. This same holding device contains the button, which being a heavy trigger (i.e. press hard to activate), moves the entire device within your hand. If at any point in time I left my thumb on the ball during a click event, my thumb would move the mouse away from its target, and thus miss the mark.
    - I had to remove my thumb from the ball rest it on the side of the device to stabilize it while I pressed the trigger. It wasn't difficult, just a bit annoying.
    - Button. Finger has to hold device and press the button simultaneously. (walk)
    - Needed to separate the tasks of moving the cursor and clicking (not really a problem, just something I needed to learn).
    - Need to hold/press the button hard while dragging otherwise it stops dragging which can be annoying.
    - Main button required too much force to drag and I found sometimes it would drop the square while using only one hand.
    - Too easy to accidently release trigger.
    - Easy to let go of click whilst making rapid movements of ball with thumb.
    - Button released at unexpected time with finger release.
    - A lot quicker thumb/finger movement meant that you had to focus on not moving your finger off the button.
    - Need to hold/press the button hard while dragging otherwise it stops dragging. (walk)
    - Need to hold/press the button hard while dragging otherwise it stops dragging which can be annoying
    - Walking made previous problem (letting go of click) slightly more sensitive. (walk)
    - Button released at times not expected - needed more pressure. (walk)
    - Sometimes found it difficult to keep finger on the trigger while moving the ball. (walk)
    - Pressure required to press button over longer periods of time (walk).
    - Not much besides the button pressing.
    - Main click - more 'solid' on/off of button. (walk)
    - Squeezing trigger.
    - Only a single button (although not really important for the experiment).
    - Button needed to be held firm, dropped accidently at times.
    - The button is required to be pressed a little harder than I would have liked
    - Button needs to be firm (walk).
    - Lack of peripheral to grip, securing the device with a single finger and avoiding excessive pressure from activating the button was a minor learning challenge.
    - Occasionally when pressing the button I would inadvertently move the mouse just off the target.
    - Button press sometimes caused jitter.
    - I found it hard to keep my arms still to click a target accurately.
    - I'd often accidentally move the mouse as I clicked, missing the target.
- Ball movement
    - Inertia of ball movement to ball movement too slow.
    - Inertia of ball too free.
    - The ball may be, or response action is too small. To move from point a to b over a long distance would require many thumb movements.
    - The ball did not always move the cursor, it may just be dirty!
    - Cursor distance per revolution of the ball too slow.
    - Moving ball, button press.
    - Sometimes found it difficult to keep finger on the trigger while moving the ball.
    - I lost hold of the object I was dragging too often - usually if I spun the ball quickly.
    - If I dragged it too fast, it seemed to drop the square – I'm sure I was still holding the button each time.

    - Low resistance on the ball made overshooting my target common place.
    - Ball is a bit loose and could move when letting go.
    - Trackball moves around (rattles); trackball moves when you remove your finger.
- Thumb movement
    - Several spins of the ball were required to move the cursor from one end of the screen to the other.
    - The repeated thumb movement to get the cursor from one side of the screen to the other, the other devices really only needed one movement.
    - Time taken to wheel cursor to position. (walk)
    - The repeated thumb movement need to move the cursor necessary distance - the repeated movement of the thumb affected the accuracy while walking. (walk)
    - Thumb movement too much.
    - I have limited movement in my thumb therefore some movements were very difficult. The Trackball needed the movement of thumb, sometimes twice and thrice over the ball to reach far away dots.
    - Need more than one rotation to move from one end of the screen to another (walk)
    - When some large jumps occurred it was necessary to remove my thumb from the device and make multiple moves to the target.
    - Needed to use a large range of thumb movement.
    - When the distance was large, it requires repositioning thumb on ball for a second movement. This transition causes error.
    - Starting with the thumb in a central position on the ball, most movements seemed to require slightly more than one roll sideways, requiring the thumb to return to the initial position and repeat the movement; this is somewhat tiring for the thumb.
    - The ball has to go multiple rotations to go from one end of the screen to the other end.
    - Thumb movement too much.
    - Erratic thumb movement, overshooting.
- Movement type
    - Difficulty in selecting diagonals and far away targets.
    - Horizontal movement seemed slightly inaccurate.
    - Also trackball creates difficulty in selecting far away targets or targets on a diagonal.
    - I noticed I had a tendency to move it horizontally and vertically rather than diagonally.
    - Diagonal movement seems somewhat hard to perform compared to horizontal or vertical movement.
    - Good for course movement but not so good at fine movement, making selection of smaller targets difficult.
- Accuracy, precision and sensitivity
    - Sometimes imprecise movement.
    - Over shot target sometimes.
        - You can easily move the mouse too far.
        - Easy to oversteer.
    - It is lack of accuracy for pointing.
    - Slow movement to aim at near target is difficult.
    - Minute cursor adjustments are frustrating to perform because of the speed of cursor movement. The Trackball device is not stable enough for precise control if held only one-handed; supporting the working hand with the other makes is the most comfortable and easy device to use overall. The cursor sometimes sticks after prolonged use.
    - The cursor moves a bit fast so that it is hard to point the position accurately.

  - Getting a firm grip to keep it steady.
  - Little bit too fast and made it somewhat hard to target.
  - Too fast - often overshot target; pressing button awkward at first.
  - Felt inaccurate - small movements resulted in great cursor movements.
  - Inaccurate movements.
  - Hard to perform precise per-pixel movement, was fine for large target selection.
  - Not much detailed accuracy.
  - Inaccurate.
  - It did not always respond to every input. (walk)
  - Walk was more difficult - the accuracy varied. (walk).
  - Very sensitive, hard to position accurately.
  - A little too slow in terms of sensitivity (walk).
  - Ball sensitivity different to what I am used to.
  - Too slow/insensitive.
  - While moving the sensitivity seemed a little high as I frequently dropped the square. (walk)
  - The sensitivity of the mouse could be faster (walk).
  - Sensitivity of the ball.
  - The trackball is very sensitive.
  - Too sensitive/no feedback, button presses a bit awkward.
  - Too sensitive so not good for fine control.
  - Sensitivity was a big issue.
  - Sensitivity too high.
  - The ball's sensitivity.
  - Sensitivity of the ball.
  - The ball tad too sensitive.
  - Too sensitive.
  - The ball wasn't as sensitive as it could have been.
  - Lack of fine sensitivity.
  - Very sensitive. Easy to overshoot targets. Unwieldy.
  - The sensitivity was not good for distance and accuracy. (walk)

Fatigue and pain

- Thumb
  - Very quickly tires the thumb.
  - A slight pain in the thumb while holding/dragging - not really a problem.
  - Thumb had minor discomfort using trackball from session 3 onwards.
- Fingers
  - Little finger squeezed the air, it becomes tired too fast.

Form Factor

- Design, comfort and fit
  - Uncomfortable x 3
  - The grip - have to clutch it in the forefinger, extended away from palm. Would prefer a design that could be held in the crotch of the thumb and forefinger, with the ball further away.
  - You cannot adjust the device to suit your hand. For me, the trackball hole for the pointer finger was too big.
  - Often, repositioning my hand to be able to grip the trigger caused the cursor to move.
  - Small hole for finger - had to hold it side-on.
  - Poor construction - often 'slipped'. Had to be held in an uncomfortable way to prevent 'slipping'.

    - Did not feel like it fitted in my hand nicely - the button was a bit awkward to press.
    - Too light weight.
    - Holding is not comfortable since it has less part to hold.
    - Not comfortable to use with one hand.
    - Had to use left hand to support my right whilst using it. Very uncomfortable to use it first on the finger.
    - A hand is occupied at all times, touchpad you can use your hands when not interacting.
- Handle length
    - Too small grip.
    - Handle should have been longer.
    - Yes, the grip was too small. Pressing the button required pressing device into palm.
    - No more place to hold.
    - Using only two fingers to hold and operate.
    - Hard to grip with one hand.
- Size
    - Too small x 6
    - The device is too small for large hands.
    - Size did not fit.
    - The size of the overall device made pressing the button while moving the cursor slightly difficult i.e. I feel if the device was larger it would be easier to manage.
    - The device was small - a target one would help it be firmly held. Perhaps attached to hand.
    - Small size == difficult to keep device stable.
    - Device not large enough to grip firmly.
    - The small size of the device.
- Ball
    - Ball felt too small.
    - Ball feels like it should be firmer in the socket.
    - The ball is able to be pressed in about a mm (during use) then it pops out again when you take your thumb off. This causes the cursor to move a few pixels. A ball that didn't have this might be more accurate
    - The ball felt a tad loose.
    - Ball is too big.
    - Design is slightly flawed - moving the finger inadvertently moves the trackball.
- Button position
    - Pressing the buttons was uncomfortable.
    - There is something about the position of the button that bugs me.
    - Not being able to 'rest' my index finger on the trigger button without fear of clicking.
    - Button. Finger has to hold device and press the button simultaneously. (walk)
    - Button is pressed opposite base of thumb, which has to have some freedom to rotate the ball.
    - The position of the button is not quite comfortable for me.
    - Location of button not comfortable.
- Wire
    - Wire.
    - The wire sometimes got in the way.
    - Cable or infrared.

Improvement Suggestions (from participants)

- Adjustable sensitivity.
- Make it more comfortable.
- Tighten the ball so there is more friction to reduce the effects of momentum. Use a joystick type handle for better grip.
- Change of size.
- Rest for arm and hand PLEASE!! And some kind of handle for little-finger. (walk)
- If the button press could be a bit smoother, it will make the operations more comfortable.
- The ball movement as described above.
- Bigger grip.
- Tighter ball so movement while walking won't move it.
- More ergonomic - make it a lot more comfortable.
- Bigger device.
- Perhaps replace the switch with pushing on the ball.
- Wireless.
- Size of trackball should be adaptable to size of hand.
- Trackball mouse needed a longer handle and more buttons.
- Nothing x 2.

Gyroscopic Mouse Qualitative Responses – Advantages / Like

Usage - General

- Ease of use
  - Easy to use x 8
  - Felt natural x 4
  - It was quite easy to get into the rhythm of it with enough practice.
  - I found that the gyro was easier to pick up and use but is hard to master.
  - Liked everything.
  - Once I worked on that holding it vertically makes it much easier I was able to use it. (walk)
  - It was my favourite while stationary, but I could hardly use it while moving. (walk)
  - When stationery, it worked moderately well. (walk)
  - Still enjoyed the freedom of use. (walk)
  - It's fun to use.
- Speed of use
  - Felt faster
  - Fast
  - Speed
  - Actual dragging was very fast.
  - Quick x 2
  - One of the fastest and more accurate of the devices.
  - Speed of the mouse - which in this case (walking) was not all that useful.
  - Quick and easy - 'point and click' approach. Use wrist rather than one finger.
  - Point 'n' click style.
  - Was quick for large target selection.
  - It is fast.
  - Is very fast, far presentation very good.
  - The operation speed is very good.
  - Fast coarse movement.
  - Quick to move large distances on screen.
  - Speed of use.
  - Speed usage.
- Effort required for operation
  - Easier to move whole hand than fingers.
  - Easier to move directly to target without overstretching.
  - Move the cursor to anywhere on the screen.
  - Very direct.
  - It was almost like pointing hand.
  - Responds well to movement.
  - Use whole arm for better precision.
  - Just wrist moving.
- Smoothness during operation
  - Very smooth and responsive to small movements without seeming erratic.
- Intuitive and familiar
  - Easy to handle, very intuitive.
  - Felt very intuitive x 10
  - Fast to learn and with more time/experience would become a more preferred input device.
  - Easy to get the hang of.
  - Familiar feel.
  - The intuitive nature of pointing. (walk)
  - It felt like a wii mote (sort of).

    - Easy to learn.
    - It's quite intuitive to use your arm to point at things.
    - It has the same feel as a mouse.
    - Quite easy to pick up and use.
    - Gyro felt quite natural for large target selection.
    - Felt similar to 'pointing' at targets.
- Novelty
    - Interesting input device.
    - Coolness factor.
    - Feels futuristic; physically involved with input device - feels more engaging.
    - Novel
    - Moving your arms feel like being more active instead of first sitting in front of the computer.
- Nothing
    - Liked nothing x 14
    - Liked nothing while walking x 7

Cursor Movement and Button press

- Cursor movement
    - Control of cursor movement easy.
    - Quick movement.
    - Fast movement.
    - Cursor speed was fast - the unit is very responsive.
    - Good for big movement.
- Button press
    - Simple to press button and cursor movement.
    - Easy to hold, no cord, felt very intuitive and easy to click the button without moving it while the Gyro on button was still pressed.
    - Back button.
    - Button click and the back button.
    - Button was easy to push.
    - Options (let go of trigger to select target).
- Accurate, precise and sensitive to use
    - Accurate x 5
    - When standing its fast and accurate really only requiring a single wrist movement to fine the target.
    - Relatively accurate when performing stationary tasks.

Fatigue and pain

- *No comments received.*

Form Factor

- Design, comfort and fit
    - Comfortable to hold x 6.
    - Comfortable to hold x 4 (walk).
    - Easy to hold x 3
    - Feels comfortable to use x 2
    - The shape, and consequently the position of the hand, is familiar.
    - The freedom of use, and it was comfortable to hold.
    - An appropriate size which made it quite easy to manage.
    - The position of the buttons made them easy to manage.
    - No uncomfortable hand-grips, easy to hold and use.
    - Buttons were very easy to use. (walk)

    - Fits nicely into the hand. (walk)
    - Handheld. Fits nicely in the hand.
    - Easy to grip and manipulate.
- Wireless
    - Wireless x 13.

Gyroscopic Mouse Qualitative Responses – Disadvantages / Dislike

Usage - General

- Ease of use
    - Take a while to get used to it. Hand is hurting after use.
    - It was the hardest of the devices to learn to use correctly.
    - Took some time to get used to but was easy after that.
    - It was just hard to get used to the movement.
    - Mouse has to be very stationary otherwise activation button needs to be released (weird to control).
    - Once I found that you release the movement button and then click and hold the left button it was OK.
    - When you use this device, you have to figure out frequently which finger is for controlling cursor and which finger is for pushing button.
    - I had to get very much used to having to activate it with an extra button.
    - Frequently changing fingers for cursor and button.
    - Having to remember to hold the *trigger* button to move the cursor, but this stopped being an issue when I got used to it after a while.
    - Nothing - but took a while to get used to.
    - Feeling incompetent.
    - Having to move the mouse in a 2D plane was difficult at first but I quickly got used to it.
    - Conceptually a new idea so I had to really think about what to do each time I picked it up before falling into a pattern, then it's okay.
    - Understanding how to manipulate the mouse to move the cursor left and right in position.
    - Understanding how to manipulate the mouse to get the desired movement on the display.
    - There were when first learning but I was able to learn to overcome them.
    - It is hard to operate at initial period before getting used with it after three sessions.
    - Operational use.
    - Performance too hard.
    - It is not easy to use as the mouse.
    - Found Gyro vertical axis unintuitive at first - expected inversion however quickly adjusted.
- Effort required for operation
    - Holding arm out in an unnatural way.
    - Expected cursor to point where I was aiming, intuitively. Hand started shaking after prolonged use. Hand moves on trigger press.
    - Hand had to be stretched in various directions.
    - Sometimes you have to move the arm quite far for reaching the target.
    - Too much arm movement.
    - A lot of arm movement.
    - There is no reference point to hold onto to keep the device steady while using it. This made it an effort to hold it still.
    - Lack of coordination.
    - Too much arm/wrist motion for simple tasks.
    - Required a lot of effort over time.
    - Needs more focus and concentration and higher operating level.
    - Requires large wrist/arm movements.
- Usage time
    - I would dislike having to use it for more than a few minutes at a time.
    - Hard to use after an extended period of disuse.

- Walking – hard to use.
    - Having to walk with and click with a rhythm! (walk)
    - Mostly uncontrollable (walking).
    - Very hard to use and impractical with walking.
    - Had to be very slow/almost stop to use it (walking).
    - Almost everything else (walking).
    - I had to stop each time I wanted the device to work - very slow walking pace! (walking)
    - The crazy movement. (walking)
    - Very difficult to coordinate while walking - too slow and imprecise. (walking)
    - Sensitive while walking (walk).
    - Not easy to use while body is moving
    - Really only feasible for stationary use (walking).
    - I had to keep re-centre it because it would be a little out when I changed hand speeds
    - Free movement.
    - EVERYTHING! Very hard to use. (walking).
    - Unusable (walking).
    - Everything, can't be used while walking normal speed.
    - Reacts to fast body movements. Hard to get into a rhythm of pressing and releasing the 'go' button.
    - I have to get used to releasing the trigger when I turn.
    - Can't control it moving, may cause difficulty under certain conditions, wind etc.
    - Wrist position and walking very difficult to operate this device.
    - To work good with it you first have to get used to release the movement button before clicking. When you turn holding the cursor button the movement of the mouse is unpredictable.
- Everything x 2
    - A lot.
- Nothing x 5.

Cursor Movement and Button press

- Cursor movement
    - Unsteady cursor movement.
    - Required pointing from the wrist vs. the arm.
    - Harder to drop (especially small target).
    - The movement in general was difficult.
    - Jitter - effort to keep arm steady.
    - Hard to zero in on the target.
    - I found it difficult to keep it level to my palm because it is too sensitive found difficult to control the cursor movements - sometimes forgot to press the button to move the cursor but tried to move the device itself - give me too much exercise to the wrist.
    - You name it, fine motor control.
    - Body/head movement affects cursor position, rather than just the arm.
    - At times seems hard to control the position of the cursor.
    - Body movement (i.e. head) caused mouse cursor to be off target.
    - Only getting used to the orientation and movement of the cursor as it is in mid-air.
    - Making small corrections to the position of the pointer difficult - had to guess the object and move it around a larger area before repositioning it.
    - Placing cursor in correct location.

  - Have to press the button to move cursor. It wasn't accurate. Movement was too jumpy.
  - The cursor was bouncing too much, needed to focus more and coordinate with arm and wrist.
  - Had to get used to it; large movements required - direction of movements not always intuitive.
  - Sometimes required wide movements, difficult to make small cursor movements.
  - Had to constantly re-adjust alignment with body.
  - Similar to trackball, movement was often 'jittery' and made hard for per-pixel selection.
  - Issues with drift occasionally caused discomfort.
  - You must move your wrist too much, you need for this mouse a lot of training.
  - Fine movement very hard to control making small target selection much more difficult than other devices.
  - Hard to do fine movements without supporting hand or arm holding gyro mouse.
  - Inaccurate in fine detail; moves slightly when you remove finger from trigger button; sometimes drifts in random directions.
  - Motion control x 2.
  - Too quick in the cursor movement.
  - Difficult to navigate to targets.
  - Hard to navigate to target, difficult to select small targets, need to keep entire body 100% still with no shakes or movements.
  - Tracking left and right movement can become difficult.
  - Jitter, low response when wanting to move per-pixel.
  - Hopeless for fine movement, required uncomfortable motion in attempting to achieve small target selection.
  - Fine control only achieved to some degree by supporting gyroscopic mouse holding arm.
  - Lack of detail accuracy – cursor wobbles.
  - Shaky use.
- Button press
  - The button to turn it on and off would possibly be better using a switch so you don't have to keep your hand clenched.
  - Thumb button press is not ideal, the button did not always respond.
  - Having to keep a button pressed while moving the cursor. I sometimes got confused between having to drag and having to move the cursor.
  - Coordinating - holding 2 buttons while moving it around.
  - Clicking with the thumb was confusing (i.e. usually use index finger on mouse).
  - Always pressing the movement button makes it sometimes complicated if the starting position wasn't the centre. Mouse click with thumb quite uncomfortable.
  - When seated, it is easy to brace the arm against the body in order to impart enough stability to the device that a click may be performed without releasing the trigger button; when standing, this is a lot harder. Because the index finger supports the device, it is difficult to release the trigger for more accurate clicking without moving the cursor away.
  - I can only think of one improvement which is pressing and releasing the button on the bottom to activate the mouse, instead of holding it the whole time. I found myself pressing the button on the bottom the same way I was using the one on top: i.e. pressing and releasing at the same time.
  - Pressing the button was easy but I had to twist my wrist awkwardly in order to move the cursor.
  - Too many buttons to press at once.
  - Too sensitive when clicking.
  - Releasing the trigger often caused the mouse to move slightly.

    - Hard to keep still for clicking.
    - Sending the message to your finger then to your thumb can be quite different and can take a bit of getting used to.
    - Pressing the button was ok, but not the selecting you make too much with your wrist and sometimes I need two hands for the selecting.
    - Clicking buttons.
    - Pressing buttons.
    - Buttons are too sensitive and cursor movement too inaccurate.
    - Thumb not a particularly good clicking finger.
- Walking – cursor movement and button press
    - It sensed every movement I made, even when I did not move my arm. (walk)
    - Very difficult to control the cursor while moving. (walk)
    - Trying to aim the swaying cursor while walking. (walk)
    - Very hard to use when moving. (walk)
    - Lack of control while walking. (walk)
    - Any movement caused the mouse to react - making the system unusable (walking).
    - Too much movement (walking).
    - Timing - the collection of square and dropping of it (walking).
    - Pretty much everything - no control, hard to stop to get close to anything (walking).
    - trying to use it while moving
    - It is no good when walking. The body motion while walking and turning significantly impacts the accuracy.
    - It moves way too much whilst walking and is affected when turning around. You have to keep your wrist very steady to be accurate
    - Interference in motion.
    - No control while walking - very difficult to be accurate
    - Too sensitive to use while walking
    - Changing direction while trying to select a menu moved the cursor - too jumpy
    - Trying to maintain control of the cursor - very hard while moving (walk)
    - Too sensitive, difficult to be accurate and move cursor (walking).
    - I found it difficult to align and aim the cursor while moving, as that would affect the cursor.(walking)
    - Because of its design, it picked up footsteps as cursor movement which made it very hard to use. (walking)
    - Sensitive to every motion of the body. Made it impossible to use at normal walking pace: Had to slow down significantly and even stop at times. Could not use it all while turning around. (walking)
    - Movement made it near impossible to move the cursor to where you wanted it to be. (walking)
    - Since it's spatially oriented was very difficult to select, drag and drop. (walking)
    - Any movement at all interacted with the gyroscopic mouse - the natural gait of walking made its use difficult.
    - Extremely jumpy when moving (walking)
    - Moving both yourself & the blue square was a challenge. My movement with the button. Was not very desirable. (walking)
    - Yes - while walking - moves cursor back and forth. (walking)
    - Hard to use while walking, since the gyro mouse is always moving as well. (walking)
    - When moving hard to control cursor position. (walking)
    - Arm & hand moved a lot with walking, difficult to control, too much movement with cursor. (walking)

    - Far too sensitive, the movement due to walking was enough to make the cursor go haywire. Walking speed ridiculously slow. (walking)
    - Yes, while moving it was almost impossible to control. (walking)
    - Jumped around, hard to pin point. i.e. hard time gaining control. (walking)
    - I found this to be the most difficult - hand / eye coordination flew out the window. (walking)
    - It was all over the shop while walking! (walking)
    - Moving the cursor while changing direction /movement was difficult. (walking)
    - It was difficult to! Too sensitive to sue while walking. (walking)
    - Yes - the movement of me walking and the sensitivity of the mouse made it difficult to be overly accurate. (walking)
    - It moved when you did making it impossible to use when walking
    - It uses gyroscopes - hence any motion of your body influences the position of the cursor - so it's hard to use when moving.
    - During walking it is very inaccurate.
    - When walking, the device is very difficult to use. If not moving in a straight line (i.e. turning) it was impossible. The cursor was too affected by my movement
    - Gyro + walking = badness.
    - Body movement interferes with mouse movement.
    - Movement caused the cursor to move making it very difficult to control. Had to make heavy use of the trigger to ensure the cursor didn't move at wrong times. It seemed to have inertia to. I would turn around and re-enable the trigger but the cursor would move even though i had stopped
    - Drift when moving.
- Accuracy, precision and sensitivity
    - When moving your head around it causes slight movements in your arm which makes it slightly harder for accuracy.
    - Sensitive and too difficult to use.
    - The highly sensitive nature that even a click for the mouse moves the cursor away from the dot.
    - It is difficult to be very accurate. Practice may resolve that.
    - Precise movement is sometimes difficult.
    - Very sensitive and not accurate.
    - Far too sensitive.
    - A bit jerky when trying to do high precision movement.
    - Not great for accuracy.
    - Too sensitive with smaller sizes.
    - It was too bloody sensitive.
    - Very sensitive to hand movements. I found I needed two thumbs to keep it steady.
    - Bit too sensitive especially while on the go.
    - Having to realign my arm and wrist in case I moved the cursor strangely. I had trouble controlling the sensitivity of the cursor movement.
    - Device was OVER sensitive - especially when objects were small.
    - Sometimes a little bit shaky, hard to position accurately.
    - Very sensitive and required too much high precision to move cursor to exact spot.
    - Yes - it was so sensitive which made it difficult to control the cursor movement.
    - Sensitivity too high with motion.
    - Motion sensitivity really hard to click small buttons without taking finger off the back button (to stabilise pointer).
    - Sensitivity of motion control.
    - Too sensitive x 4.
    - Too sensitive to the movement of hand and wrist making the pointer shaking resulting in low accuracy when target was small.

  - Sensitive for every movement of wrist, arm and should makes it harder to select tiny target.
  - Sensitive for the minor movement of hand, wrist and arm, making it hard to select tiny dot.
  - Sensitivity, easy to over or undershoot target.
  - With no resistance to work against, easy to overshoot and float over the target.
  - Very sensitive to the movements of your hand.
  - Holding mouse in the air made mouse susceptible to body tremors, making selection difficult.
  - Very shaky too sensitive.
  - Hard to make a right aiming.
  - Too hard to control the pointer when selecting tiny dot.
  - Accuracy is hard.
  - Difficult to maintain accuracy.
  - Fine movements were hard.
  - You have to stay still during use.
  - Too easy to miss.
  - The over-shoot effect seemed to make the accuracy a little poor for dot selection.
  - Movement felt a little fast and sometimes felt as though it was over-shooting the target.
  - Selecting targets is challenging.
  - Inaccurate at times; no feedback.
  - It was too difficult because it was not so accurate and hard to work with it.

Fatigue and pain

- Arm
  - Arm got tired very easily.
  - Arm soreness, can't control whilst moving.
  - Arms: I could not have used the Gyroscopic Mouse much longer as my arm muscles felt quite fatigued.
  - It is strenuous on the upper arm, forearm and wrist muscles; as a result it takes little time for the movement to become ragged.
  - Extended use makes arm sore.
  - When arm became tired it became necessary to reset cursor start position as could not rest arm.
  - I experienced some minor shoulder/arm strain while using the gyroscopic mouse.
  - Holding out my arm to align the gyroscopic mouse caused some minor strain on my shoulder.
  - Ache in hands / arm from gyro use.
  - Sore arms.
  - Caused a little bit of strain on the biceps.
- Hand
  - Hurt hand after a while.
  - Hand was hurting while holding the Gyroscopic Mouse for a while.
  - The arched thumb position for the Gyroscopic Mouse is also markedly uncomfortable.
  - Some pain in the wrist/fingers with gyro and use.
- Wrist
  - Painful in wrist.
  - I hurt my wrist today (prior to test). The Gyro-Mouse aggravated it.
  - Wrist pain after long use.
  - Hard on the wrist.
  - Painful on the wrist, holding positing needing to be changed frequently.
  - Sore wrists.

    - Discomfort in wrists after gyro mouse.
- General
    - Muscle fatigue.
    - Really started to ache. (walk)
    - The pain was due to the use of gyroscopic mouse.
    - The pain was there when I tried to use the move with the gyroscopic mouse.
    - Only when using the gyro mouse - I felt tired - maybe just because I didn't like it.
    - Slight fatigue in use, required higher hand eye coordination.

Form Factor

- Design, comfort and fit
    - No relaxing of the hand during usage.
    - The physical shape made it harder from time-to-time to control the device.
    - It was uncomfortable.
    - Not ergonomic.
    - Didn't feel natural in my hand.
    - Shape is pretty inconvenient.
    - The hand has to remain in a certain (not-relaxed) position all the time.
    - Mouse click with thumb quite uncomfortable.
    - Clicking with the thumb was confusing (i.e. usually use index finger on mouse).
    - Design suggests usage similar to a normal mouse, however the button cannot be reached there. Needs to be redesigned if both buttons are to be used.
    - Does not sit properly in the hand. Similarly to trackball, it has problems with stressed little finger (not too bad though).
    - A gun shaped handle might have been easier. Consider fencing foil orthopaedic grip for example.
    - Button position based on shape of unit.
    - It is not comfortable for the wrist.
    - As a left handed user, I found the device difficult to hold and operate.
- Size
    - Large in hand.
- Weight
    - Heavier than other mouse.
    - Slightly heavy.

Improvement Suggestions (from participants)

- Blender.
- Compensate for movement of head/arm when walking.
- Use a closed feedback loop with additional sensor on the users' body to correct unwanted motion.
- No.
- Not really, the problems are fundamental to its design (the fact that is gyro).
- Bring its sensitivity to a more controllable level.
- Don't use it while walking.
- Error cancellation (cancel erratic movements).
- Stability control.
- Get rid of it.
- Drive over it in a car.
- Smaller more stability.
- Gyroscopic mouse perhaps would be better to only respond to translation through space not rotation or reduce the sensitivity.
- Gyro-Mouse would be better for selecting things in the real world (but I haven't tested that).

- Why not a Gyroscopic Mouse shaped like a joystick? (Maybe all it would take is to switch x-y axis?) That way you can move once and it will continue to move.
- I would love to see a Gyroscopic Mouse that is not affected by movement such as walking.

Twiddler2 Mouse Qualitative Responses – Advantages / Likes

Usage – General

- Ease of use
  - Easy to use x 5
  - Easy to control.
  - Easy to use once I was used to it.
  - Easier to use than the Gyroscopic mouse.
  - The ease of using the little knob.
  - The control stick is so simple to use. With personal fine-tuning of this instrument, I feel it could be very effective.
  - The thumbstick was very easy to operate.
  - It was better than nothing.
  - Very easy to control the thumbstick. (walk)
  - Felt I had more control over the device, as opposed to the touchpad & gyro mouse. (walk)
  - Similar to mouse and trackpad, relatively easy to use.
  - Easy to pick up.
  - Easy to navigate with and select targets.
  - Trackstick was simple to use and easy to learn.
  - Simple to operate.
  - Easy to operate once the technique was learnt.
  - Felt like I was improving.
  - The Twiddler2 was initially hard to use but I improved and got used to controls over time.
  - Easier to use for long periods.
- Speed of use
  - Fast
  - Speed
  - It was very fast.
  - The speed and performance are good.
  - The operation speed and the selection are good.
  - Reasonably quick for large distances.
- Effort required for operation
  - Only needed a small range of thumb movement.
  - It was hard to accidentally jostle the thumb twiddler but not too hard to move.
- Smoothness during operation
  - Smooth control while walking (walk)
  - Smooth movement, good for slow tasks.
  - Very smooth.
  - Smooth movements and able to achieve good accuracy.
  - Smooth cursor movement, good fine control with practice.
- Intuitive and familiar
  - Mouse and the little button was similar to my laptop mouse.
  - Not a lot - although it is intuitive.
  - The mouse part was familiar.
  - Similarity to trackpoint controls on laptop.
  - Reasonably intuitive for some laptop owners.
- Not affected by movement/walking (walk)
  - Not affected by walking. (walk)
  - Movement did not affect its use as it did the gyroscopic mouse. (walk)
  - Stable during body movement. (walk)
  - It was the exact same walking, no adaption necessary (walk).

    - Not my favourite device however I was surprised that I was able to use this whilst walking. (walk)
- Single handed use
    - Could brace it against my hand without losing accuracy.
    - Could keep arm against torso for support.
    - Only needed one hand. (walk)
    - Could hold my hand by my side and operate it fine. The other devices had to be held up in front of me.
- Functionality
    - Its range of functions.
    - Possibility of a whole keyboard. Not much else really - could be great with plenty of practice.
    - Multi-use.
    - Multi-use (walk).
- Nothing
    - Nothing x 15
    - Nothing while stationary.
    - Not a lot when walking.

Cursor Movement and Button press

- Cursor movement
    - Stable / consistent mouse motion during both the walking and stationary experiments.
    - Very smooth and precise, not at all erratic.
    - Reasonably smooth cursor movement.
    - Cursor movement is extremely easy, even for tiny adjustments. It is the least tiring of the devices for the thumb.
    - The just right freedom of the red dot and high accuracy in movement.
    - Smooth movement to target.
    - The cursor is easy to control (direction).
    - No erratic cursor movement.
    - Easier than the gyro - was easier to control while walking probably because it's not overly sensitive.
    - Fine control, little movement.
    - Smooth cursor action.
    - Cursor movement is generally comfortable.
    - Cursor and buttons.
    - Smooth cursor.
    - Trackpoint is stable and cannot be effected by hand shaking.
    - Trackpoint.
    - Easy to move cursor.
    - Control of cursor was accurate - easy to make small adjustments.
    - Jittered a lot less.
- Button press
    - Concept of pick up / drop down click.
    - Easy to click without moving cursor.
    - If selecting things that are orientated to the head display, I prefer the Twiddler.
    - Buttons.
    - Pointer is stable when clicking the target.
    - The design made it easier rather than uncomfortable to press buttons close the pointer device.
- Movement type
    - Easy to move in single direction.

    - Pull down menu - as it was very easy to push the trackpoint up then down a little rather than moving sideways.
    - It is easy to move cursor horizontally or vertically.
    - Pull down menu - moving down is easier with thumb.
- Accurate, precise and sensitive to use
    - Direct.
    - Accurate x 5
    - Quite precise after a while of training.
    - High precision when you get used to it.
    - Good degree of sensitivity.
    - Reliable.
    - Sensitivity of the mouse part.
    - Sensitivity.
    - Felt relatively accurate.
    - Can be very precise.
    - Can be quite accurate if light enough.
    - Low sensitivity of the knob was good for fine grained selection.
    - Very responsive for both gross and fine pixel selection.
    - Reasonably accurate for small distances.
    - Accurate, hard to accidently click / move cursor.
    - The accuracy. x 2.
    - The sensitivity of the trackpoint was good.
- Thumb movement
    - The thumb movement is better than the trackball - one gesture as opposed to a couple.
    - It is just a constant thumb movement to move the cursor. (walk)

Fatigue and pain

- When arm was tired you could drop arm to side.

Form Factor

- Design, comfort and fit
    - Comfortable to hold x 4
        - It being more comfortable than the gyro mouse.
    - Attached nature.
    - Similar to handle like the trackball.
    - Fitted to hand.
    - Easy to hold.
    - I can hold it nicely.
    - Gotten used to holding it. Feel more at ease using it. It sits nicely in the palm.
    - Comfortable to grip.
    - Slipping it on.
    - Easy to hold.
    - The concept of the joystick was good - but the sensitivity needs to be adjusted.
- Size
    - Okay size.

Twiddler2 Mouse Qualitative Responses – Disadvantages / Dislikes

Usage - General

- Ease of use
    - Hard to control.
    - Somewhat harder to use.
    - Action.
    - Nothing while stationary. It was frustrating to use the slowest of devices for me.
    - Yes - the whole experiment - this device is hard to use let alone trying to walk/move whilst in use! (walk)
    - Too fiddly.
    - General use.
    - Unable to use more easier to access triggers.
    - Longer learning curve.
    - Hard to handle because of the position of the fingers and thumb at the back. Hard to reach the button on the front. You have to learn how to handle it.
    - Initial set-up of this device is annoying at best. Once it is set up and user familiar with it, it is very simple to use.
    - Was not intuitive.
    - Controlling mouse/movement halfway down thumb takes a while to get used to.
    - General awkwardness. (walk)
    - Same as standing still x 2 (walk)
    - Is not good for work.
- Speed of use
    - Mouse seemed too slow, and not easy to drop on target.
    - Twiddler is slow.
    - Very slow.
    - Slow movement.
    - Slow movement between targets, hard to achieve fast, coarse movement.
- Interaction technique
    - Also the issue of switching between mouse and keyboard made it annoying.
    - A lot of work on one finger.
    - Switching between the mouse /keyboard aspects.
    - The device in the middle to move the cursor and the fact that I have to hold it with my left hand to stabilize the use of the device.
    - Keyboard mode slows down drags a lot!
    - Using normally unused fingers for control.
- Affected by movement/walking (walk)
    - Same problems as stationary but more due to movement. (walk)
    - Very hard device to manoeuvre and even hard whilst walking. (walk)
    - Walking made the use of the twiddler difficult. (walk)
    - Slight movements affected mouse movement. (walk)
- Everything x 3
- Nothing x 3

Cursor Movement and Button press

- Cursor movement
    - Hard to handle you have to concentrate how to move the cursor.
    - Cursor sensitivity.
    - Corrective movements difficult, slow to move.
    - Control of cursor with thumb. (walk)
    - Accurately stopping the cursor is challenging.
    - Cursor movement too imprecise.

    - Very hard to press and move the cursor.
    - Having to make small movements made it difficult.
    - Not easy to control the cursor smoothly and accurately. Both cursor movement and selection were troublesome.
    - Thumb not ideal for fine control.
    - The 3rd button to navigate was way too sensitive.
    - Nipple idea with movement is difficult not natural with grip.
    - Yes - the device used to move the cursor was extremely difficult to manoeuvre
    - Found it difficult to maintain pressure on the A key while using the thumb to move the cursor.
    - Cursor button was not accurate.
    - After moving the cursor to the right place, pressing the button, was a little bit difficult.
    - I found I could only move the mouse very slowly or very quickly - no happy medium. Bend the finger and move the cursor was not easy all the time.
    - Found it difficult to move cursor with trackpoint reliably and uncomfortable pressing button (due to its location).
    - Trackpoint isn't sensitive like a mouse.
    - Sensitivity of the touch stick proves a steady learning curve that lead to rewarding results.
    - Difficulty moving the pointer to the appropriate location was very difficult.
    - Requires a very light touch which sometimes I forgot causing me to overshoot targets.
    - Requires a light touch.
    - Takes a bit to get used to the finesse required to achieve accurate selection.
    - Movements can be a bit extreme/fast.
    - Can be all over the place.
    - The scroll button was ok, but if you push the button too hard so the cursor to fast and if you push the button not so hard it was too slow and not fluent.
    - Applying pressure to key and knowing when to release during walking. (walk)
    - Difficult to point in required direction.
- Button press and (button press and move combination)
    - The press button and the movement.
    - Many times I pressed the buttons accidently.
    - Adjustment of finger positions (even clicking) usually moved the pointer making re-adjustment necessary. I even had trouble sometimes clicking the large 'OK' button.
    - I would go to press the D key, but that would make my thumb move slightly and send the cursor to the other side of the screen.
    - Button presses are tricky.
    - Pressing button was awkward but overall functionality was okay.
    - The drag button required movement in between individual press to register.
    - A key and D Key reverting to keyboard made too annoying - remained with E key, but had to hold it down the whole drag - there is no double click.
    - The D key was the easiest to use as I didn’t have to think about it while I was moving the cursor, but my pinkie could barely reach it. Also, a lot of the time it did not seem to register that I have pressed the D key, it did not pick up the square and I could not tell if it had or not.
    - Clicking button and mouse at the same time - would often move the mouse unintentionally.
    - The key isn’t very easy to press and the nub sits in on uncomfortable place on my thumb.
    - Activating/deactivating mouse made it inconsistent.
    - Pressing the button.

  - Difficult to press button and move cursor at same time (device is little too big).
  - Sometime the D key would not pick up the blue block, so some mouse movement needed again and sometimes thought I had it but I didn't.
  - Press / move combination - very difficult.
  - Hard to press E key and walk and drag mouse. (walk)
  - Found it difficult to maintain pressure on the A key while using the thumb to move the cursor. (walk)
  - The positioning of the D Key sometimes made it difficult to press. (walk)
  - Movement required between the drag buttons clicks. (walk)
  - Inconsistent behaviour when jumping into mouse mode. (walk)
  - The buttons are in an awkward place. To press a button you need some force on the other side of the device. Typically this is the thumb on the trackball. So you first need to move the thumb before pressing a button or the cursor will move.
  - Had to hold my finger in an awkward position to press the E key.
  - Have to get the right grip otherwise the force of pressing the button can move the whole device.
  - Pressing the button was difficult. x 2
  - Buttons are in a difficult position.
  - Key is hard to press.
  - A and E buttons are close making missing point. And the button is not sensitive for the pressing - I have to press hard.
  - Other keys may interfere the E key if both of them being pressed at the same time.
  - Left handed - needed a more ergonomic trigger rather than the E key.
  - Hard to reach around and click properly.
  - Finger didn't naturally align with the A or E buttons.
  - Sometimes the button is not function you must move the mouse again and then it is function.
  - Button press required more force than desirable, multiple no-registered presses.
  - Clicking is hard.
  - As a left hand oriented individual, i needed to constantly think about not depressing the incorrect key.
  - Inability to use a more comfortable key (as a left hander).
  - Button location.
  - Pressing buttons is difficult if device isn't strapped in completely.
  - Button presses. A more sensitive button would be suitable for me.
  - Movement made it more difficult to press the button and trackpoint accurately. (walk)
- Accuracy, precision and sensitivity
  - Least accurate of the input devices for me.
  - To slow and not overly accurate.
  - Accuracy if you want to do tasks fast.
  - The joystick-type part was difficult to push accurately.
  - Acceleration factor - moving fast leads to missing target.
  - Inaccuracy of thumb knob - speed differential is too erratic.
  - The trackpoint sometimes hard to judge - sometimes you over shoot the mark - sometimes you don't give it enough.
  - Low accuracy when pointing tiny dot - button is too numb.
  - The joystick was too sensitive.
  - Not sensitive to its acceleration but just to its position. (walk)
  - Thumb movements need to be very controlled, making it easy to go too far if one slips. The sensitivity of the joystick thingy.
  - Trackpoint too sensitive.
  - Acceleration sensitiveness of the trackpoint. (walk)

    - Sensitivity.
- Not really x 2.

Fatigue and pain

- Fingers
    - Had some pain in my fingers/arm because the twiddler was operated using my thumb and the other fingers had to be on the E all the time.
    - Was a slight pain the in fingers whilst navigating with the end button. (walk)
    - Twiddler Mouse was not comfortable and caused slight pain in fingers.
    - Twiddler almost gives me a cramp in the fingers. Buttons were too close for long fingers.
    - Some pain in the wrist/fingers with twiddler use.
- Thumb
    - The device did not fit comfortably, I could not brace it and use the A or E keys and move the cursor together, it strained my thumb.
    - Thumb got tired because it was bent sharply to get to the stick. (walk)
    - Simple finger fatigue (the one used to move the twiddler). (walk)
    - Moving the cursor for the Twiddler Mouse required too much force and the lower part of the thumb hurts/gets fatigued easily.
    - Thumb and hand cramp after a while.
    - Thumb cramp.
- Wrist and hand
    - Strain on hands. (walk)
    - Hurts the wrist.
    - When using the Twiddler Mouse, I felt pain in my hand.
    - Twiddler required a very unnatural hand position to push button.
    - Hands: The awkward position of the Twiddler's button caused some forces of pain in the palm and in the back of the hand during and after use.
- General
    - Using it was strenuous.
    - Fatigue.
    - The pain was due to the use of the twiddler mouse x 2.

Form Factor

- Design, Comfort and fit
    - Awkward grip x 2
    - Twiddler would be better if one's hand wrapped around it better.
    - No comfortable way of holding the mouse. No comfortable way of pressing the button.
    - Very clumsy and uncomfortable to use.
    - I think the shape of a rectangle is not 'ergonomic' enough.
    - Shape.
    - Uncomfortable, would be much better if it was more ergonomic.
    - Hard to hold and had to be careful to press the right button.
    - The ergonomics of the device felt very poor.
    - It was uncomfortable to hold x 3
    - Had too many buttons, was not ergonomic.
    - Just not the right size for my hand.
    - Awkward to hold and use x 2.
    - Too hard to hold! Very uncomfortable in the hand.
    - Awkward to hold, not designed for long nails! (walk)
    - Its design was hard to hold and use. (walk)
    - Not ergonomic - too many keys, no natural position to use, not intuitive. (walk)

    - Uncomfortable. (walk)
    - The design of the mouse does not seem ergonomic - making it difficult to hold and operate.
    - The strap. (walk)
    - Fingers are slightly cramped on the buttons
    - Awkward finger positions x 4
    - General design - clicking a button on one side pushes it against my thumb, making the pointer move off the target. (walk)
    - Holding it.
    - Hard to hold - hard to control due to the fact it was hard to hold! (walk)
    - Comfort to buttons/knob.
    - The design of the device - it was never made to fit a human hand.
    - Having no place to rest fingers without chance of pressing a button. Hard to firmly attach mouse to hand.
    - The device did not fit comfortably, I could not brace it and use the A or E keys and move the cursor together.
    - Unable to comfortably hold as it was not flexible to hand size.
    - Size and shape of device and location of buttons.
    - Bad design, cramps the hand to use directional button but leave finger on select button.
    - Position of bar and button.
    - Mouse needs to be hand moulded so the whole hand doesn't have to move to either move the cursor or press the button.
    - The design of the mouse does not seem ergonomic - making it difficult to hold and operate.
    - How the band was wrapped around the knuckles made an impact on the usefulness of the device.
    - Very unfirm fitting. Inappropriate for my particular hand and finger size. Some buttons just inoperable.
    - Didn’t suit my hand at all, if felt very awkward to use.
    - The position of the keys together with the joystick made it difficult to operate.
    - How the strap was attached made a difference to the systems accuracy and usability. (walk)
    - The shape of the device put the thumb at a weird angle and made it difficult to move the cursor.
    - It's tricky to get the strap adjustment perfect.
    - Not really - it didn’t fit my hand very snugly though.
    - You can't see the buttons.
    - Buttons were hard to access without losing grip of the device.
    - Placement of fingers was a bit awkward.
    - Awkward shape to hold.
    - Not comfortable.
    - Awkward to handle.
    - Uncomfortable. x 2.
    - Awkward shape.
    - How the band was wrapped around the knuckles made an impact on the usefulness of the device.
    - Twiddler mouse can be more handy if it's fixed to something. For support.
- Button size and placement
    - Button is too small. There are too many buttons on the device. Too small to grip it and keeping the finger on the button.
    - The awkward position of the keyboard.
    - Button positions were cramped.
    - The buttons were too close.

  - Too many buttons that can accidently be pressed.
  - The positioning of the buttons.
  - Button placement. x 2.
  - Buttons get in the way, no difference to discern against different types of buttons. Odd holding angle.
  - The button was hard to press.
  - Difficult button placement and awkward thumb control.
  - The button. (walk)
  - Design of buttons near top made them hard to press. (walk)
  - Fingers hard to be curved very tightly to be ask to operate the buttons.
  - Position of buttons.
  - The button locations simply suck.
  - The buttons at the front are awkward.
  - Uncomfortable to hold especially if using the E key.
  - The buttons were too close and the position was not natural.
  - Position of the button made it difficult to press.
  - Button is uncomfortable to reach if hand is too big.
  - Button to select was hard to press (i.e. avoiding the buttons nearby).
  - Difficult button placement. Under-hand device.
  - Button placement poor - buttons where fingers rest. Twiddler at odd position - ergonomics should be more like a hand grip but buttons are in the way.
  - The button is in a difficult position when the TM is held firmly in the hand. The button is VERY awkwardly positioned and occasionally fails to respond when touched too lightly (the ring finer not being by far the strongest finger). As I have quite a long hand and fingers, the strap falls over.
  - My knuckles and is therefore almost unusable; a bracing hand is needed to provide the necessary stability.
  - Buttons poorly designed - difficult to reach mouse button.
  - The push button is too small.
  - Buttons are bad. Impossible to use. (walk)
  - Button difficult to reach.
  - Too many buttons makes more confusing.
  - Button size.
  - Pressing buttons – awkward.
  - Trigger finger position.
- Trackpoint placement and usage
  - Trackpoint seemed based on geometry rather than comfort, had to hold it with slight pressure against the Velcro strap while pushing the button or remove the thumb from the stick.
  - The joystick and the location of the mouse select keys requires the use of a non-dominant finger, greatly angering me on long exercises.
  - Cursor button is too small. Moving the cursor and pressing the buttons is uncomfortable.
  - Fixed position of pointing control to grip.
  - Trackpoint itself is not very comfortable but useable.
  - Using thumb on such a small mouse.
  - Nipple x 2.
  - The "twiddle stick" felt too far right to grip it properly, a joystick style grip would be better.
  - Not used to the trackpoint.
  - Trackpoint should be bigger. (walk)
  - Joystick far too small. A longer (even only 1 cm) stick with a contoured head to fit and lock in the thumb would have been better.

    - Its physical size made it hard to control the joystick which in turn controls the cursor location.
    - Cursor button way too sensitive.
    - Pointer movement.
- Size - general
    - It was too small and had an awkward shape.
    - Device too small x 2
    - Big x 2.
    - Bulky x 2.
    - Size. x 2.
    - Device a little large to control and hold. (walk)
    - Too small for my hands - hard to reach the keyboard buttons as a consequence.
    - Device is little too big.
    - Bulky controller.
- Weight
    - Felt a bit heavier than the others.
- Wire
    - Cable got in the way sometimes.
    - That it was connected via wires.

Improvement Suggestions (from participants)

- More ergonomic design for holding.
- Improve comfort, button position.
- Shape should be changed to joystick like shape.
- An ergonomic shape would make it much more usable.
- Larger frame.
- Adding a twiddler mouse to the form-factor of the trackball.
- Make it comfortable to use - move the buttons on shape the unit to fit nicely in a hand.
- More hand comfort.
- Reduce size.
- More ergonomic.
- A cylindrical type object with the click button on the side would make it a more relaxing experience.
- I think the twiddler has a lot of potential, it was just that the position of the buttons were really bad. I think that if the trackball device had the thumb control of the twiddler it would be a pretty nifty device.

Touchpad Qualitative Responses – Advantages / Likes

Usage - General

- Ease of use
  - Easy to use x 15
  - Easy to use x 6 (walk)
  - Easy, only had to worry about the one input device (the screen) instead of several buttons - the less buttons/input devices the better.
  - Easy to control.
  - Simple x 3
  - Simplicity, drag & drop.
  - Easy to select targets.
  - Got use to easy and with the correct technique can be of great use.
  - Simpler.
  - I really liked the touchpad x 2
- Speed of use
  - Quick x 2
  - Move quite fast
  - Fast x 3
  - Target selection easy, moves at a speedy pace.
- Effort required for operation
  - Generally quite easy to use with little force required.
  - Less effort.
- Smoothness during operation
  - Smooth x 2
  - Smooth (walk).
- Intuitive and familiar
  - Quickly grew accustomed to it.
  - Intuitive x 10
  - Used to touchpads thus easy to operate.
  - Very familiar x 9
  - It was the familiarity of use with current techniques.
  - Very easy to use, much like the touch pad on the laptop. I liked this one by far the best.
  - Remind me of a laptop touchpad - therefore had experience using it - easy to use!
  - Very familiar (walk).
  - It is like using a touchpad on a laptop - very familiar x 7.
  - Have used them before - familiar with it's sensitivity etc.
  - Used to it.
  - Easy to learn x 2
  - Easy to learn and use.
  - It was simple to understand.
  - Used a touchpad on a laptop prior to tests, simple to apply experience across to the wrist version.
  - Simple to learn and master.
  - Familiar to use.
  - Felt familiar with device.
  - It is easy to understand for travelling with a notebook it is ok, but not for work.
- Not affected by movement/walking (walk)
  - Movement did not affect it - it became the easiest one to use. (walk)
  - Not effected by movement. (walk)
  - Walking made very little difference to operation. (walk)

    - It was intuitive and not susceptible to movement, making it accurate whilst in motion. (walk)
    - Similar to use when standing. (walk)
    - Same as standing still. (walk)
    - Possible to use. (walk)
    - Fairly easy to use while moving. (walk)
    - Easy to use whilst walking - again familiarity. (walk)
    - Very easy to use. (walk)
    - Consistent behaviour whether stationary / walking.
- Nothing. (walk)
- Everything
    - Everything of touchpad is my favourite.
    - Everything.

Cursor Movement and Button press

- Cursor movement
    - Very responsive to small corrections / movements.
    - Hybrid device. Cursor movement depends on finger movement, not time of acting. Cursor stay on its place when finger is off the pad.
    - Ability to guide / control the cursor.
    - The accuracy of moving the cursor. (walk)
    - Good control of pointer - even for small motions. (walk)
    - Perfect control. No problems with dragging or clicking. (walk)
    - Ability to control / guide cursor. (walk)
    - Easy to get one object to another while walking - easy to control. (walk)
    - High accuracy, good responses.
    - You can stop cursor movement easily - you can hold your arm still even when you move.
    - Easy to control the pointer.
    - Low sensitivity and low movement made small pixel selections easy.
    - Same accuracy for gross and fine movement.
    - Good for both coarse and fine grained movement.
    - Quick for large movements, reasonably accurate for small movements.
    - Jittered a lot less.
- Button press
    - Operating the button for click and drag was very simple.
    - Everything. Using thumb to click served as an anchor - established a relative distance for drag n drop.
    - Double tap controlled movement.
    - The buttons seems responsive enough.
    - Good for pressing and pointing.
    - Tap function.
- Accurate, precise and sensitive to use
    - Accurate x 7
    - Accurate (walk)
    - I could brace my hand and stay fairly accurate. (walk)
    - Can use my thumb support my fingers for greater accuracy. (walk)
    - Sensitivity x 3.

Fatigue and pain

- Minimal arm and shoulder pain.

Form Factor

- Design, comfort and fit
  - Very comfortable.
  - Comfortable easy arms/hand position. (walk)
  - Comfortable to use x 4.
  - Most comfortable.
  - It is comfortable and fast but no so comfortable as a mouse.
  - Does not get in the way when not in use.
  - Simplicity.
  - It was at hand without being in hand.
- Weight
  - Light and unobtrusive.

Touchpad Qualitative Responses – Disadvantages / Dislikes

Usage - General

- Speed of use
  - Slow and difficult to use; requires more coordination than I possess.
  - Isn't the best device for speed / responsive-ness buttons / movements need to be in two actions move with two fingers - click with another.
- Interaction / attachment technique
  - Hold arm up to use it.
  - Two hands are occupied, but if you can afford that, no problems.
  - Both hands are in air, without any rest.
  - No rest for arms. (walk)
  - 2 hands position (walk)
  - One arm, holding arm up. (walk)
  - Had to hold arm up.
  - Both arms required.
  - Not having one hand free (e.g. while sneezing).
  - Having to hold up both arms to operate it.
  - Required both hand for input.
  - Had to use both arms / hands to operate. (walk)
  - Keep my left arm elevated throughout the experiment. (walk)
  - There is no place to rest the hand. (both hands in seal)
  - Fitting on the body, instead of left wrist would be better. (walk)
  - Mounting to the wrist wasn't solid so would alter slightly while using it. (walk)
  - Requires both hands to use. x 3.
  - Tedious to hold wrist in same position.
  - Holding arm in the same position can be strenuous.
  - Arm mounting.
  - Required two hands to operate, small movements significantly influenced accuracy which was a problem standing.
- Affected by movement/walking
  - Quite difficult to use while walking - slow (walk)
  - Needed to see to walk but also had to continually glance at pad. (walk)
  - Arm less stable when walking (still reasonably stable) (walk)
  - Overall I just had to concentrate harder to complete the experiment. (walk)
  - When walking, it requires both arms to be still, making it harder to use.
  - Speed of mouse - a little? To move with it as it required 2 hands. (walk)
  - Both arms moving while walking meant sometimes finger left the surface. (walk)
  - Requires 2 hands (1 hand & 1 wrist). Normal arm motion while walking makes it awkward to use - had to hold my left hand with by 3rd, 4th fingers of right hand to stable? It with my 1st fingers, to keep them relatively 'locked'. (walk)
- Nothing
  - Nothing different than stationary x 2 (walk)
  - Nothing x 22
  - Nothing x 7 (walk)

Cursor Movement and Button press

- Cursor movement
  - I would roll my finger to gain fine cursor control. This would be slower.
  - Sometimes you roll your finger too much trying to be accurate and the cursor jumps a large distance away from where you want.
  - Cursor moves when tapping.
  - Different motion of arms while moving causes erratic movements.

    - Walking movement made my hands shake making the cursor move. (walk)
    - Moving my finger over a semi-stable surface made fine accuracy difficult.
    - Small size of the touchpad overtime requires multirole strokes to move the cursor.
    - Easy to accidentally move cursor or click; relies on relative position of both arms, movements cause inaccuracy.
    - Minor fault on identifying double click for movement.
- Button press
    - Using pad for clicking didn't work so well during walking. (walk)
    - When walking, it's easy to accidentally click – tap. (walk)
    - Sometimes single tap did not respond.
    - Double tapping did not always enable dragging i.e. not calibrated for my style of double clicking.
    - Trying to hold the button and drag can be rather annoying as it was rather uncomfortable.
    - Due to moving my arms relative to each other both, keeping the button clicked for dragging and keeping the cursor steady was difficult while walking. (walk)
    - Sometimes if you tend to touch the pad unintentionally because of its sensitivity, it may end up selecting the wrong selection.
    - Took me a while to get used to the single tap concept - doesn't work if you use more than one finger.
    - Touchpad single tap sometimes didn't register click.
    - Single tap didn't always register which lead to unforced errors.
    - Easy to register a second tap when trying to move to next target.
    - Getting used to moving and selecting.
    - Clicks not registered if moving cursor straight after click.
    - Taps weren't registered sometimes.
    - Single tap sometimes read as a double click so i missed some targets.
    - Sometimes if you have a single tap it counts two times (double click).
    - Sensitivity of touchpad on tapping made me make a number of errors.
    - Single tapping a little too sensitive, multiple unintended taps registered.
    - Left/right click found it awkward to use them.
    - It is a little bit hard for touchpad to identify the double click for pointing and moving.
    - By operating too quickly the system registered my single tap and touch and move operation as a double tap.
    - Easy to accidentally double tap (incorrect registering) and register incorrect selection.
    - Single tap very sensitive. Left click inconvenient.
    - Double click caused me to miss targets.
    - Occasionally would register tap-down but not up, so I would move to next target and release - performing the click on the wrong target. Mental effort required to make sure it didn't happen.
    - Sensitivity of tapping.
    - Tapping too sensitive.
- Accuracy, precision and sensitivity
    - No. Perhaps increasing the sensitivity slightly.
    - Not really - possibly care of the sensitivity of it but it would be complaining if it was too sensitive. (walk)
    - Not as accurate.
    - Final accuracy is hard to get.
    - Not as accurate, however much better than the gyroscopic mouse. (walk)
- Space on pad
    - Sometimes reach the edge. Respond, moving the pointer unexpectedly.

  - Ran out of space if not double clicked in the right position.
  - Pad was too small, often ran out of room when attempting to drag over long distances. As a result, dropped target too soon and hard to pick them up again.
  - Run out of room on the pad. (walk).
  - Pad was too small, often ran out of room when attempting to drag over long distances. As a result, dropped targets too soon and had to pick them up again. (walk).
  - The distance between two points to big you must change your finger position sometimes.
  - You have only a short distance to move from point A to B.

Fatigue and pain

- Arm
  - To suspend left arm for use which was a little tiring.
  - Experienced some fatigue in the arms.
  - Experienced some wrist & arm fatigue. (walk)
  - Too much strain on my arm - fatigued very quickly from holding it out in front of me.
  - Slight soreness in arm when using touchpad.
  - As I had to hold it up when using touchpad.
  - Arm fatigue.
  - Wrist fatigue, I cannot see prolonged use.
- Fingers.
  - Strain on fingers.

Form Factor

- Design, comfort and fit.
  - The Velcro came off the wrist strap.
  - It wasn't fastened securely and it moved. (walk)
  - Not comfortable x 3.
  - Button Placement.
    - Buttons awkward to press.
    - Position of the buttons with respect to the pad could be more ergonomic.
  - Not very stylish.
  - Possibly its position on the hand/wrist.
- Size
  - Bulky.
  - Little big when stepping.
- Wireless or infrared.

Improvement Suggestions (from participants)

- Remove cable, clamp tap to last moved position.
- Buttons with better touchpoint / response.
- More rigid mounting or mounting elsewhere on the body.
- Improve pressure clicking on the touchpad.
- I like the concept but did not like strain on my arm. perhaps it could be positioned elsewhere / not sure where though.
- Maybe mount on leg.
- Could the touchpad be placed on the upper arm so that arm can be passive - but means active arm need to reach further.
- Before creating device, it would be nice just count all forces acting during operation. Mainly used operations acts in a way, then device just try to 'run away' of its place. Hands

must be in rest all the time, which is not necessary for operation, but they are in stress all the time. No exception.