

The Effect of the Light Necessary for Space Horticulture on Emotion and Cognition



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Declaration

This thesis contains no material which has been accepted for the award of any other degree or diploma in any University, and, to the best of my knowledge, this thesis contains no material previously published except where due reference is made. I give permission for the digital version of this thesis to be made available on the web, via the University of Adelaide's digital thesis repository, the Library Search and through web search engines, unless permission has been granted by the School to restrict access for a period of time

Abstract

Successful human space exploration is physically, mentally, and psychologically demanding. With plans to have more human activity in space and for longer periods of time, maintaining crew health and wellbeing is becoming more challenging. Space use horticulture systems are currently being developed which help with providing nutrients, oxygen, and waste recycling. However, it is mostly unknown how exposure to these systems may affect people psychologically. While exposure to nature has been associated with reduced stress, increased cognitive performance and positive emotion, there is a range of emerging literature which identifies mixed effects from different LED environments. To date, no published studies were identified that investigate the psychological effect of the unique qualities of relevant horticulture systems. Utilizing a within-subjects design, this study will compare the short-term effects of sitting near two small horticulture models: one with the light optimized for plant growth, the other, a normalized white light. Effects for emotion will be measured via the Positive and Negative Affect Scale (PANAS), vigilance via the Psychomotor Vigilance Test (PVT) and cognitive performance under stress via the Montreal Stress Imaging Test (MIST). Direction of effects were not hypothesized. Results from 30 participants primarily ran using linear mixed effects models indicated no significant results. Key strengths, limitations and implications were discussed and include providing preliminary results and methodology which can inform the development of psychologically sensitive space plant systems.

Keywords: light, plant, cognition, emotion, vigilance, stress

The Effect of the Light Necessary for Space Horticulture on Emotion and Cognition

Human activity in space is physiologically and psychologically demanding (Pagel & Choukèr, 2016). Crew members are subject to a myriad of adverse factors, including the absence of gravity, natural diurnal cycles and natural biophilic environments, limited communication, isolation, confinement, high level of professional workload, monotony and proximity to hostile environments (Gushchin et al., 2019; Odeh & Guy, 2017). The psychophysiological impact of space exploration is rarely studied during missions, however, researchers have utilized long-duration spaceflight analogue studies, such as the Mars500 (Wang et al., 2014) or Antarctic winter over studies for this purpose (for critical review see Suedfeld, 2018). Negative impacts recorded from these analogue environments included neurocognitive changes, fatigue, misaligned circadian rhythm, sleep disorders, altered stress hormone levels, immune modulatory changes, reduced positive emotion, and symptoms of depression (Pagel & Choukèr, 2016). As missions increase in duration such as the Artemis lunar, Gateway, and Mars missions, understanding crew health, wellbeing and performance in these harsh environments is critical for success (Wenzel, 2021).

Space Plant Systems

One vital component to successful long term space exploration is the use of plant-based life support systems (hereinafter referred to as space plant systems) (Fert et al., 2002; Medina, 2021). The need for readily available food is evident (Wheeler & Tibbitts, 1987), as food supplies can only sustain crews for a limited amount of time. Resupplies are not only non-viable but expensive, space and time consuming which leaves less room for habitation equipment and scientific research (Galluzzi et al., 2006; Brown et al., 2021). Therefore, since 1971, over a dozen plant cultivation experiments have been conducted on manned missions (for review, see

Zabel et al., 2016). To date, most research has aimed to develop fundamental functions, like providing nutrients and oxygen, reducing carbon dioxide, and waste recycling while overcoming the challenges of growing plants in a space setting (Zabel et al., 2016). Currently, two experimental systems are in use aboard the International Space Station (ISS), the Vegetable Production System commonly referred to as “Veggie” and the Advanced Plant Habitat (or the APH; Massa et al., 2016). Horticulturists are still investigating the optimal light for plant growth, including for different plant processes, species, and purposes. However, most state-of-the-art systems like “Veggie” use wavelength specific LED lights. These aim to provide light optimal for the key photosensory systems that have been identified in horticultural research (for review, see Bantis et al., 2018). Of these key systems, phytochromes absorb mostly red light (600-750nm) in the spectrum, and others (i.e., cryptochromes, phototropins, and those of the Zeitelupe family) absorb blue light (390-500nm) (Bantis et al., 2018). Some plant research and systems are exploring the use of green (approx. 525nm), broad spectrum, and far-red light (approx. 730nm) (Bantis et al., 2018). However, red and blue spectral qualities are fundamental to most current systems. For example, “Veggie” primarily omits red and blue light with capability of adjustment, including an option for green light for visual purposes (Massa et al., 2016). These systems present different possibilities regarding human exposure. Whilst the APH is enclosed and tending is mostly automated, “Veggie” requires a relatively moderate amount of interaction for tasks such as manual tending activities; for review of build qualities see Massa et al. (2016) and for review of crew horticulture time see Poulet et al. (2021).

Space Plant Systems and the Biophilic Hypothesis

Space plant systems have long been cited as a potential countermeasure to the adverse conditions and negative psychological outcomes related to long duration space exploration

(Nechitailo & Mashinsky, 1996; Perchonok et al., 2012; Massa et al., 2016; Neilson et al., 2021).

The biophilia hypothesis is the primary rationale for these citations, which posits that there is an innate relationship between humans and nature (Ulrich et al., 1991).

A substantial amount of empirical research has found exposure to nature can improve psychological health (Corazon et al., 2019; Gaekwad et al., 2022; Van den Bosch & Sang, 2017). A range of effect sizes can be found in meta-analyses, with research commonly utilizing subjective emotional affect measures such as the Positive and Negative Affect Schedule (PANAS; Watson & Tellegan, 1988) (Gaekwad et al., 2022; Roberts et al., 2019). Positive affect usually increases, while negative affect decreases, however, publications often exhibit a high risk of bias (Roberts et al., 2019). While some researchers still argue exposure to nature can also increase positive physiological outcomes, a systematic review of the research from the last eight years found heterogenous results (Corazon et al., 2019). It appears the physiological effects are mediated by other factors, for example, confounds in common research designs including climate (e.g., daylight exposure) and exercise (Corazon et al., 2019). Understanding the limitations of the biophilic hypothesis is critical when designing research questions regarding space use horticulture systems. While plants are often present, the environment and stimulus are substantially dissimilar to the bulk of biophilic research designs.

Space Plant Systems and the Effect of Light

The limitations of the biophilic response literature means that this study will focus primarily on light as the stimulus. The light necessary for plant growth in space is likely to produce acute effects on vigilance, cognition, and possibly emotional affect, which together are arguably more critical for crew success and more objectively measured via standardised tests. A range of meta-analyses and systematic reviews identified numerous studies indicating light

effects many human physiological and psychological functions, including pupillary response, circadian rhythm, stress, vigilance, cognition, and mood (Schweitzer et al., 2004; Siraji et al., 2021; Tähkämö et al., 2019; Vetter et al., 2022; Xiao et al., 2021). Most visual and non-visual responses to light are mediated through the eye. Light stimulates photoreceptors in the retina, including rods, cones and relatively recently discovered intrinsically photosensitive retinal ganglion cells (ipRGCs) (ref). From the retina, light information travels to the brain for neural processing via two major pathways. One employs the thalamus and the visual cortex, the other, the hypothalamus and numerous downstream connections including the septum, thalamus, midbrain, and spinal cord (Vetter et al., 2022). Importantly, the latter pathway regulates the circadian and neuroendocrine systems which are features of almost every physiological, metabolic, and behavioural system (Lucas et al., 2014; Vetter et al. 2022).

Historically, the human circadian cycle has evolved to be directly entrained by the light-dark phases in the 24-hour rotations of the earth - punctuated by the rising and setting of the sun (Van Drunen & Eckel-Mahan, 2021). However, data suggests exposure to artificial lights which emit irregular amounts or at irregular circadian phases can lead to circadian and neuroendocrine disruptions associated with numerous health concerns (Cho et al., 2015; Lunn et al., 2017). This has been realized in space settings where the non-visual effects of artificial light can include a multitude of physiological and psychological outcomes which influence the health of crew member's day-like (active) and night-like (rest) states (Brainard et al., 2016; Lucas et al., 2014). The importance of appropriate light exposure is emphasized when considering the need for high performance in challenging conditions which include the lack of natural diurnal cycles traditionally regulated by the earth's light-dark cycle (Gushchin et al., 2019; Lucas et al., 2014; Van Drunen & Eckel-Mahan, 2021). Thus, in 2016 the ISS was equipped with an LED, solid-

state lighting system which has three modes; general illumination mode, phase shift/alertness mode, and pre-sleep mode (Brainard et al., 2016). While this offers a basic light intake structure which can help with circadian rhythm; stress, vigilance, cognitive performance, and emotion can also be acutely altered by artificial light with minimal impact on circadian phase (Gabel et al., 2013; Lucas et al., 2014). It is currently unknown how short-term exposure to light from space plant systems could affect crew members.

Research has explored many factors that mediate the effect of light. Vetter et al. (2022) outline the key factors of light including timing, intensity, wavelength, duration, and light history. As previously discussed, current space horticulture models and practices vary largely in relation to these lighting characteristics. However, crew members tend to “Veggie” under the general illumination mode or phase shift/alertness mode for minutes at a time and are being exposed to these light settings prior to tending (Brainard et al., 2016; Poulet et al., 2021). The intensity of the light at the eye is more difficult to estimate and has been problematic in quantifying the human response to light more generally (Knoop et al., 2019). In terms of spectrum, the red and blue wavelengths of light from relevant plant systems is perhaps the most stable characteristic, yet has not received any identified psychological empirical attention. Research has, however, investigated the acute effects of blue enriched polychromatic and blue monochromatic light on human physiology and psychology. In three recent systematic reviews, the strongest evidence suggests acute alerting effects increase with greater illuminance and/or greater dominance of short wavelengths (Siraji et al., 2021; Vetter et al., 2021; Xiao et al., 2021). Alertness is often measured by subjective ratings and objective reaction time measures; most commonly the Psychomotor Vigilance Test (PVT). Souman et al.’s (2018) earlier systematic review quantified the effect of intensity in polychromatic white light but found mixed results for

blue light compared with controls of other wavelengths. However, research in this area has increased since that study, with short wavelength research gaining greater empirical attention in subsequent years (Siraji et al., 2021).

Numerous studies have also found blue light effects higher cognitive function and emotion, although effects share large covariance with other factors (Siraji et al., 2021; Xiao et al., 2021; Münch & Bromundt, 2022). Siraji et al.'s (2021) recent systematic review found some studies reporting increased higher cognitive function under blue light compared to controls, although the effect depended on task complexity, time of assessment, and control light properties. Substantial evidence has been collated to demonstrate the acute effect of blue light at night-time (Cajochen, 2007). This evidence adds to the growing theory in the literature which posits the non-visual purpose of light is to help govern the circadian rhythm and thus general human function (active through to rest states). This is a vital consideration when investigating complex psychological processes such as higher cognitive function and emotion. In one study using functional magnetic resonance imaging (fMRI), participant responses to emotional stimuli increased in the voice area of the temporal cortex and hippocampus under blue light compared to green (approximately 525nm) (Vandewalle et al., 2010). This revealed an acute influence of wavelength on emotional brain processing (Vandewalle et al., 2010). However, when emotion is measured subjectively via self-report (the bulk of research using positive and negative dimensions), findings are often heterogeneous (Xiao et al., 2021). A large moderator of the emotional effect of blue light is the time of day, with morning exposure yielding the most consistent increases on positive affect (Xiao et al., 2021). Research has indicated that blue enriched light is as effective as a much brighter white light in the morning when treating Seasonal Affective Disorder (Meesters et al., 2011). However, some research suggests both blue

and red light can improve mood even at night (Plitnick et al., 2010). For the current study's context, the literature is emerging and limited. For example, light studies are often underpowered, include unaccounted covariates (Siraji et al., 2021), and reviews often group results of differing methods and stimuli. Furthermore, long wavelength (red) light is seldom studied but is sometimes used as a control, indicating effects are still present relative to darkness but seemingly smaller relative to shorter wavelengths of the same illuminance (Plitnick et al., 2010).

Current Research

The only identified study to investigate the effect of space plant systems is currently being conducted by the National Aeronautics and Space Administration (NASA) (Massa et al., 2018). It is investigating the behavioural health component in ISS crew members who tend to "Veggie" with anecdotal evidence and biophilia theory as rationale. Proposed outcome measures are subjective and include the Profile of Mood States Short Form (POMS-SF) and the custom made Veggie Questionnaire (VQ), along with recording International Personality Item Pool (IPIP-120) and demographic information (Massa et al., 2018). To date, this is the only identified empirical study that aimed to investigate the psychological effects of a space or indoor plant system. While research has investigated different monochromatic light and polychromatic broad spectrum white light or sunlight, to date, there are no published studies investigating the psychological effects of the light spectrum necessary for space or indoor horticulture (usually polychromatic blue and red, pink/purple appearance) nor on the general environment produced by these systems. The study aims to measure a wide array of important outcomes directly guided by this review. It will include measures of emotional affect due to the commonly recorded general emotional decline and cases of emotional lability. Emotional arousal due to these

environments causing increase in distress and irritability towards ground control and other crew member staff; as well as a critical decline in vigour and motivation. Vigilance due to the risk of fatigue and critical lapses of attention. Cognitive performance under stress due to the great importance of crew members remaining at peak levels, through the myriad stressors that have been reviewed (Sandal et al., 2006; Massa et al., 2016; Pagel & Choukèr, 2016; Gushchin et al., 2019; Odeh & Guy, 2017).

Aims and Hypotheses

The aim of the current study is to assess the effects of light optimised for plant growth on human emotion, cognitive performance and performance under stress. In order to control for a range of covariates, including human and light characteristics, only the spectral quality of the light will be manipulated. Two main conditions will be created where participants are to be assessed: one with light spectrum deemed necessary for indoor plant growth (referred to as ‘plant’) and a control condition using white light of the same illuminance analogous to standardised human lighting (referred to as ‘control’). This study adds to the literature by filling an important gap in knowledge which will help guide comprehensive, psychologically informed lighting design in space and on earth. All hypotheses are non-directional due to the empirically novel characteristics of the plant light condition.

The hypotheses of this study are:

1. There will be a significant effect of light condition (plant compared with human) on change in affect as measured by the Positive and Negative Affect Schedule.
2. There will be a significant effect of light condition (plant compared with human) on change in emotional arousal as measured by the Subjective Units of Distress Scale.

3. There will be a significant effect of light condition (plant compared with human) on change in: number of lapses, number of false starts, reciprocal mean reaction time, fastest ten percent reaction time and median reaction time on the Psychomotor Vigilance Test.

4. a) There will be a significant difference in percentage of accurate responses measured during the Montreal Imaging Stress Test between the plant light condition and the human light condition.

4. b) There will be a significant interaction between stress condition (stress compared to control) and light condition (plant compared to human) on percentage of accurate responses measured during the Montreal Imaging Stress Test.

Method

To address the above hypotheses, the current study employs a fully within-subjects experimental design. Participants were exposed to two different LED conditions; 1) light deemed necessary for plant growth and 2) a white light control. The order of the conditions was counterbalanced between participants. Dependent variables for emotional affect were measured via the Positive and Negative Affect Schedule (PANAS), emotional arousal via the Subjective Units of Distress Scale (SUDS), and vigilance via the Psychomotor Vigilance Test (PVT). Further, within each lighting condition, stress level was manipulated using the Montreal Imaging Stress Test (MIST), creating four more conditions (training, control, rest, and experimental) and a 2 (light) x 4 (stress level) within-subjects hierarchical design. The PVT, PANAS, and SUDS were administered in that order twice during each condition, once before the MIST and once after.

Participants

The current study was the first to assess the effect of exposure to these unique set of stimuli. Therefore, there were no experiments nor meta-analyses which could be used for a useful *a priori* power analysis. Accounting for the within subject's design, linear mixed effects modelling and based on the practical rationale that in a space setting a small difference in cognitive function is meaningful, the study aimed to sample a minimum of 50 participants. However, due to equipment delays 33 were assessed with one omitted from analysis due to large amounts of missing data and two omitted due to phone use and instructional disregard during assessment.

Participants included in analyses (N = 30) were recruited through sample pools from the University of Adelaide and through the social media accounts of the researcher. Four (13.33%)

were recruited from the School of Psychology's SONA Systems application where first year psychology students were reimbursed with academic credit, five (16.67%) via flyers posted on notice boards around campus, seven (23.33%) via the researcher's post on a University's Facebook page and 14 (46.67%) via their public Instagram account. All participants were asked to contact the researcher who briefed, screened, and provided them with the participant information and consent form. Participants who did not receive course credit were reimbursed with a \$50 voucher.

Participants needed to be aged 18 to 65 years old, considered healthy, living in Adelaide and have a good level of English comprehension. To ensure participant safety and reduce possibilities of type 1 or 2 errors, participants were screened and excluded for any neurological conditions (including stroke, transient ischemic attack (TIA), or recent concussion), any neurodegenerative disease, migraine, diabetes (Type 1 or 2), any eye disease or visual impairment involving the retina, Seasonal Affective Disorder, Traumatic Brain Injury, Colour Blindness, or any other photosensitive conditions (Esquiva & Hannibal, 2019).

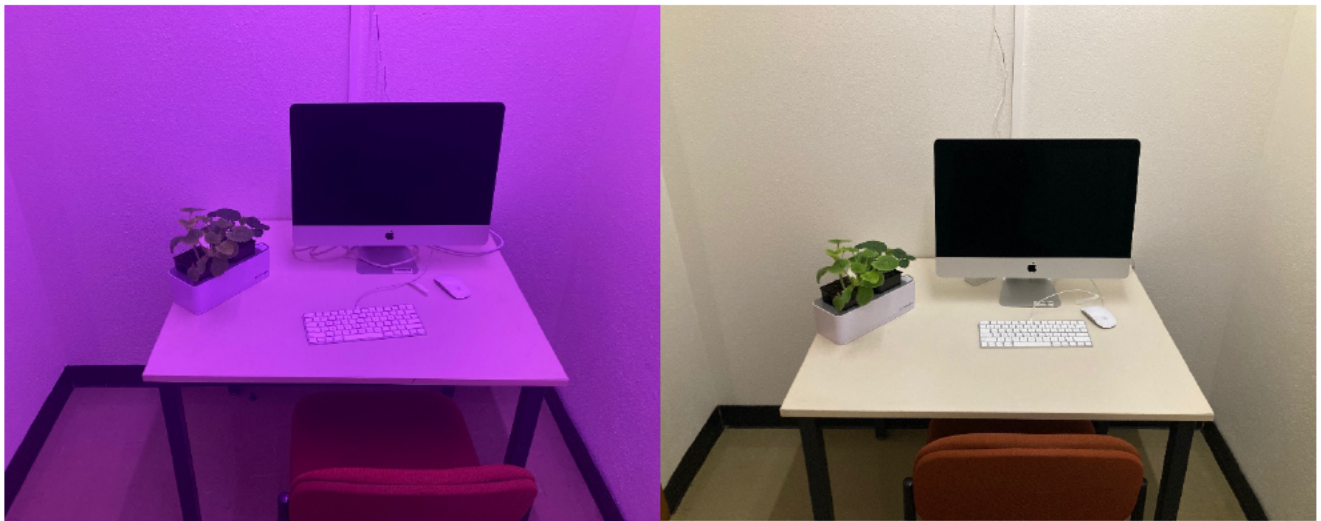
The sample comprised of 11 (36.67%) males, 18 (60%) females and one (3.33%) nonbinary participant. Participant age ranged from 18 to 33 (Mdn = 21.5, M = 22.07, SD = 3.72). Vocation between participants varied widely, the two largest categories including five (16.67%) psychology students and five (16.67%) engineering students. There were 13 (43.33%) participants who completed the assessment from 10:00am to approximately 12:00pm, seven (23.33%) from 12:30pm to approximately 2:30pm, and 10 (33.33%) from 3pm to approximately 5:00pm. All assessments were completed in Adelaide during Spring, from the 27th of September to the 1st of November 2022.

Ethics approval was granted by the University of Adelaide, School of Psychology's Human Research Ethics Sub-Committee (22/15).

Setup and Stimulus Qualities

Figure 1

From Left, Image of Plant Light Condition and Control Light Condition



The experiment took place in two fully enclosed laboratory testing rooms with standardized air temperature via air conditioning at the University of Adelaide in the Applied Cognition and Experimental Psychology Laboratory. Both the plant light and the control light condition are displayed in figure x. Inside both rooms a set of plant containers with zucchini and strawberry plants were presented under each lighting condition (see Appendix B). These plants were chosen because they are edible (a valid crop), almost odourless, and can survive relatively well without much care. Each room was illuminated using one set of LED strip lights (Wiz, LED Strip, 2 Meter Starter Kit, 1600 lm) which were attached to the ceiling in identical positions (see Appendix B). Illumination in the room was measured in three places using a digital lux meter

(model LX 1010 B). Computer screens were set to a dim but non eye straining standardised low light of approximately 10lx at vertical eye level. Light with the computer screen turned off was approximately 80lx at vertical eye level. Light at a horizontal measurement from the centre of the desk with the computer light turned off was 161 lx in the plant condition and 158 lx in the control condition. This was standardised via the Wiz light app (ref) and variation was only due to sensitivity of researcher standing position in the room, although efforts to mitigate this were applied. 161 lx was the brightest setting on the plant light mode; thus, the control white light was lowered to match. Importantly, lux at vertical eye point in the plant condition ranged from 74 to 110 ($M = 89.57$, $SD = 10.59$) and the control ranged from 73 to 108 ($M = 86.2$, $SD = 10.10$). While the lab rooms were fully enclosed, a bright white office light from the adjoining, fully enclosed room would have briefly illuminated the lab room, this occurred two times before and after instruction was given to participants during new tests. This also illustrates participant light history as they spent approximately 10 minutes in this room while being informed about the assessment and signing consent. Lastly, it is important to consider the prior light history due partly to time of day and the effects of circadian phase alignments or shifts. It is assumed most participants had prior sunlight exposure while walking the grounds of the University.

Measures

Cognitive Measures

Psychomotor Vigilance Test

Psychomotor Vigilance Tests (PVT) are reliable measures of sustained attention and alertness, commonly utilised in sleep experiments (Lim & Dinges, 2010). The PVT chosen for this study was based on Thomann et al. (2014) which was run using Inquisit software (millisecond.com, Seattle, WA). In the test, participants are instructed to press the spacebar as

fast as possible after a red stopwatch appears on screen. After a response, the screen returns to blank for a rest phase which is randomly assigned to last between two and ten seconds. A valid response (occurring after the stopwatch appears) is followed by feedback of the reaction time in milliseconds. An invalid response (false start) is followed by an error message. The test runs for approximately ten minutes. The PVT was chosen as it is a valid predictor of real-world performance (Lim & Dinges, 2010), is widely accepted in experiments investigating lighting effects (Siraji et al., 2021), and recommended by NASA when investigating crew performance relevant to the ISS and other long-term space habitation (Wenzel, 2021). Metrics included in analyses were number of lapses, number of false starts, reciprocal mean reaction time, fastest 10% reaction time and median reaction time. A lapse was defined as failing to react or reacting after 500ms.

Montreal Imaging Stress Test

The Montreal Imaging Stress Test (MIST; Dedovic, et al., 2005) was used to elicit a mild, acute stress response and to determine the effects of stress and lighting condition on cognitive performance. The MIST consists of four conditions: training, rest, control, and experimental; with training administered first and the latter three administered in counterbalanced order. In the training session, which lasts approximately five minutes, the participant's ability to perform mental arithmetic is assessed. The recorded time is used to set a default time limit for the experimental condition. In the rest condition, participants are presented with the testing interface but no tasks. In the control condition, participants are instructed to solve five arithmetic problems while their performance is recorded. The same is instructed in the experimental condition but participants are subject to stressors. Programmed stressors include a problem time limit (maintains a correct answer rate between 20% and 45%), and the presence of an on-screen

performance bar, which compares the participants low performance to the “average” of between 80% and 90% correct. Further, the researcher is instructed to provide negative evaluative feedback. Research using a range of imaging methods (e.g., functional magnetic resonance imaging) has consistently mapped these components to physiological markers, validating them as stressors (Dedovic et al., 2009). In active conditions the participants are instructed to answer the problems by "dialling" via the mouse: left button (dials anti clockwise), right button (dials clockwise), middle button (submits the response). The software was programmed and presented in Inquisit 6 on a Mac Desktop computer. Metrics included in analysis were accuracy (proportion correct) and problem response time.

Measures of Emotion

Emotional Affect

Current emotional affect was measured using the 20-item Positive and Negative Affect Schedule (PANAS), a widely used self-report measure of the valence of emotional affect (Russell & Daniels, 2018; Watson et al., 1988). The schedule includes two, 10-item scales (Positive and Negative Affect) which have emerged reliably as the two dominant dimensions of emotional experience (Watson & Clarke, 1994). Items are validated adjectives associated with different feelings and emotions (e.g., distressed, enthusiastic, strong, alert). Participants indicated to what extent each item described their current mood (i.e., “to what extent you feel this way right now, that is, at the present moment”) on a five-point Likert scale ranging from 1 (“Very slightly or not at all”) to 5 (“extremely”). Total scores for each scale range from 10-50, with higher scores indicating higher levels of Positive or Negative Affect. The ‘moment’ timeframe instruction was used and is well validated and sensitive to changing internal and external circumstances (Watson & Clarke, 1994). The measure is often used in light experiments and has yielded significant acute

effects in (within an hour) LED studies (Plitnick et al., 2010; Xiao et al., 2021). The PANAS was also chosen for its strong construct validity, with convergent correlations of .90 to .95 for Positive Affect, and .92 to .95 for Negative Affect ($N > 5000$; Watson & Clark, 1994). The Cronbach's α for the Positive Affect subscale was .84 and the alpha for the Negative Affect subscale was .86, indicating high internal reliability.

Emotional Arousal

Emotional arousal was measured using the Subjective Units of Distress Scale (SUDS). This widely used scale was popularized by Wolpe's work in systematic desensitization and has generally been used to measure emotional discomfort responses to specific stimuli (Lohr et al., 1992; Wolpe & Lazarus, 1966). Participants indicated on a scale ranging from 0 (totally relaxed) to 100 (highest distress/fear/anxiety/discomfort that you have ever felt). A widely accepted framework posits emotional affect is best characterised using two dimensions; emotional valence which ranges from high positive to high negative affect (measured here by the PANAS) and emotional arousal which ranges from calming to exciting or agitating (measured here by the SUDS) (Lang et al., 1993; Russell, 1980).

Procedure

Before entering the first test room, participants were asked to read and sign the information and consent form, followed by filling out demographic information. They were also briefed that refraining from viewing any lit screen device would ensure the quality of the data. Whilst participants understood this request, it was completely voluntary, most offered to switch all devices to silent. Upon entering in counterbalanced order, participants were asked to be seated and were given five minutes to adjust to the first lighting condition (e.g., plant-light condition). During the adjustment phase, the researcher explained that instructions are standardized and will

be read from a script (see Appendix A) For each test, participants were directed to read the standardized instructions while the researcher was still present until they indicated they understood. They commenced only after the researcher had left and closed the door. Participants knocked quietly upon finishing, the researcher checked for problems, and then set up the next test. The door was only opened when the researcher needed to move between rooms. The first test was the PVT which was already set up on the screen; it took approximately five minutes. Next, participants were asked to complete a PANAS and SUDS, taking approximately five minutes. Next, the MIST was administered where the researcher was present and provided negative feedback during the experimental (stress) condition. The participant then completed another PVT, PANAS and SUDS in that order. When finished the condition, participants were allowed a 10-minute rest and reset, some used the bathroom and their phones. The same assessment procedure was then repeated in the other condition. After completing the second round of assessment, the participant was debriefed regarding the purpose of the study and granted either course credit or the voucher.

Results

All analyses were performed in R (version 4.2.2), using the lme4, ggplot2, ggdist, car, and rstatix packages (Bates et al., 2015; Kassambara, 2022; Kay, 2022; R Core Team, 2021; Fox & Weisberg, 2019; Wickham, 2016). The alpha level for all inferential statistics was set at .05.

To test the first three hypotheses a series of linear mixed effects models were fit. Each model included the effect of participant as a random intercept. Fixed effects were lighting condition: plant or control, and occasion: before MIST (1) or After MIST (2). Interactions for fixed effects were included. Potential covariates (lighting preference, time of assessment, caffeine consumption, gender, and education) were included as fixed effects during preliminary modelling using the Anova function from the ‘car’ package. Model fit was assessed via the Akaike information criterion and the Bayesian information criterion. However, both models were fit when criterion provided conflicting results. Throughout analyses, there were no significant differences between competing models, thus, estimations from the model indicated by the Bayesian information criterion were reported. This was preferred as it favours simpler models and is common practice in the field (Shmueli, 2010). The p values for all linear mixed effects models were estimated via the anova function, a function in base R (R Core Team, 2021). Restricted maximum likelihood was used as a relatively unbiased parameter for estimation for linear mixed models (Bates et al., 2014).

Effect of Light Condition on Change in Emotional Affect and Arousal

To test if there was a significant effect of light condition on change in Positive Affect a linear mixed effects model was fit. Descriptive statistics are displayed in Table 1. There was a significant main effect of occasion on Positive Affect ($X^2(1, N = 30) = 4.65, p = .031$). According to the coefficient estimates provided in Table 2, the average Positive Affect score

decreased by 1.63 in the second measurement occasion compared to the first. However, there was no significant difference in change in Positive Affect between the plant light condition and the control, this interaction is represented by Plant Condition: Occasion (2) in Table 2. Further, there was no main effect of light condition, with means varying less than one point between conditions on either occasion one or two.

Table 1

Descriptive Statistics of Emotion

	Plant				Control			
	Occasion 1		Occasion 2		Occasion 1		Occasion 2	
	<i>M</i>	<i>SD</i>	<i>M</i>	<i>SD</i>	<i>M</i>	<i>SD</i>	<i>M</i>	<i>SD</i>
Positive Affect	26.3	7.40	24.4	7.73	25.8	8.23	24.2	8.46
Negative Affect	12.8	3.04	14.4	4.17	13.4	3.51	14.0	3.55
Median	12	-	13	-	12	-	13.5	-
SUDS	23.3	2.74	28.8	3.18	22.8	2.76	25.5	3.21
Median	20	-	25	-	20	-	20	-

Note. Median reported in brackets due to normality violations

The same method was used to test whether there was a significant effect of light condition on change in Negative Affect and SUDS. The results yielded very similar outcomes, although as can be expected due to MIST stress (Dedovic, et al., 2005), Negative Affect and SUDS increased from occasion one to two. Descriptive statistics are provided in Table 1 and coefficients with p-values in Table 2. Importantly, there was no significant effect of light condition on change in Negative Affect or SUDS. Although, coefficient estimates of this

interaction effect were relatively large with Negative Affect yielding an estimate of 1.22 and SUDS yielding 2.50.

Table 2

Coefficient estimates from mixed-effects models predicting emotional outcomes

	Coefficient	Std. Error	t value	Pr(>Chisq)
Positive Affect				
Intercept	25.83	1.45	17.76	
Plant Condition	0.43	1.15	0.38	.696
Occasion (2)	-1.63	1.15	-1.42	.031*
Plant Condition:Occasion (2)	-0.23	1.62	-0.14	.886
Negative Affect				
Intercept	13.37	0.66	20.28	
Plant Condition	-0.63	0.71	-0.89	.962
Occasion (2)	0.60	0.70	0.85	.018*
Plant Condition:Occasion (2)	1.22	1.01	1.21	.225
SUDS				
Intercept	22.83	2.98	7.66	
Plant Condition	0.50	2.72	0.18	.363
Occasion (2)	2.67	2.72	0.98	.042*
Plant Condition:Occasion (2)	2.50	3.84	0.65	.516

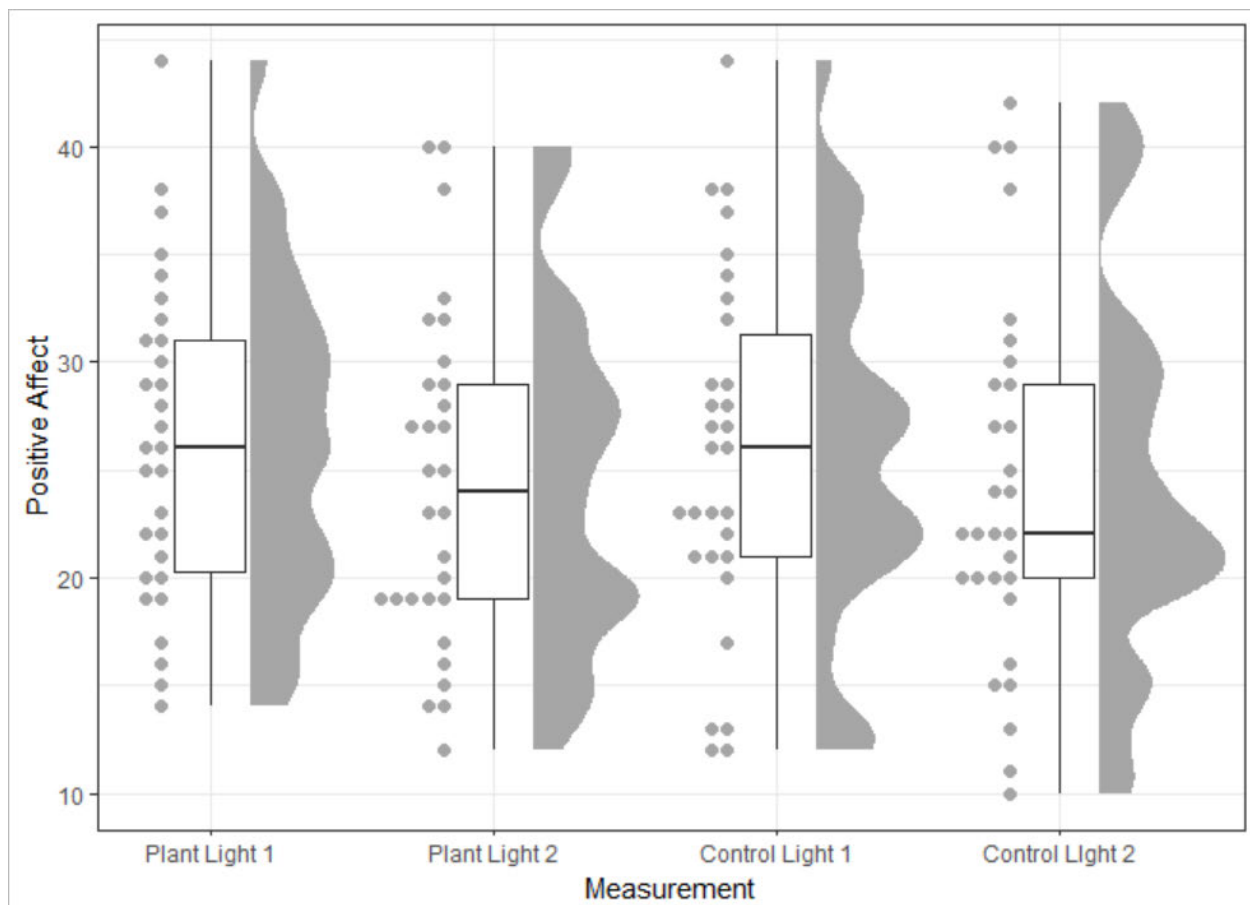
Note. Occasion (2) = second measurement in the condition, after the MIST

The current results indicate emotional measures were sensitive to occasion, with Positive Affect significantly decreasing when measured after the MIST, compared with before. Negative Affect and SUDS also changed according to measurement occasion but increased. This indicates an effect of participant fatigue, MIST, or some other external or internal factor on change in emotion. The results support the sensitivity of the PANAS and SUDS being used as acute measures of emotion (Watson & Tellegan, 1988).

It is important to note the large variability in the data, particularly the PANAS scores. For example, Figure 2 shows the variability of Positive Affect in various forms, the possible range of PANAS scores is 10-50 and as displayed the data appears flat. Thus, it is possible these models were underpowered.

Figure 2

Positive Affect Distributions Displayed in Each Condition and Occasion



Effect of Light Condition on Change in Vigilance

Once again, the same method and mixed model structure was used to test the effect of light condition on change in: median reaction time, reciprocal mean reaction time, number of lapses, number of false starts, and fastest 10% reaction time on the Psychomotor Vigilance Test.

Table 3 provides the descriptive statistics of all outcomes.

Table 3

Descriptive Statistics of Vigilance

	Plant				Control			
	Occasion 1		Occasion 2		Occasion 1		Occasion 2	
	<i>M</i>	<i>SD</i>	<i>M</i>	<i>SD</i>	<i>M</i>	<i>SD</i>	<i>M</i>	<i>SD</i>
Median	293	5.38	305	5.08	296	4.82	304	5.19
Reciprocal	0.003	0	0.003	0	0.003	0	0.003	0
Lapses	0.833	0.215	0.571	0.202	0.767	0.218	0.828	0.222
False Starts	1.14	0.303	1	0.254	1	0.267	0.69	0.158
Fastest 10%	256	3.51	264	3.51	261	3.31	262	3.45

Note. Median reported in brackets due to normality violations

Like with emotion, there was a significant main effect of occasion on median and reciprocal mean reaction time. Again, there was no significant interaction between occasion and condition, nor were there main effects of condition for all PVT indices, see Table 4. Thus, the data did not support the third hypothesis that there would be a significant effect of light condition on vigilance. However, coefficients for median, reciprocal mean and fastest ten percent reaction times all indicated that participants were faster in the plant condition overall. As displayed in Figure 3, the variance of median reaction time data was large, although appearing relatively less

flat than data from the PANAS. Further, the median and mean of median reaction time in the second occasion was slightly slower in the plant condition.

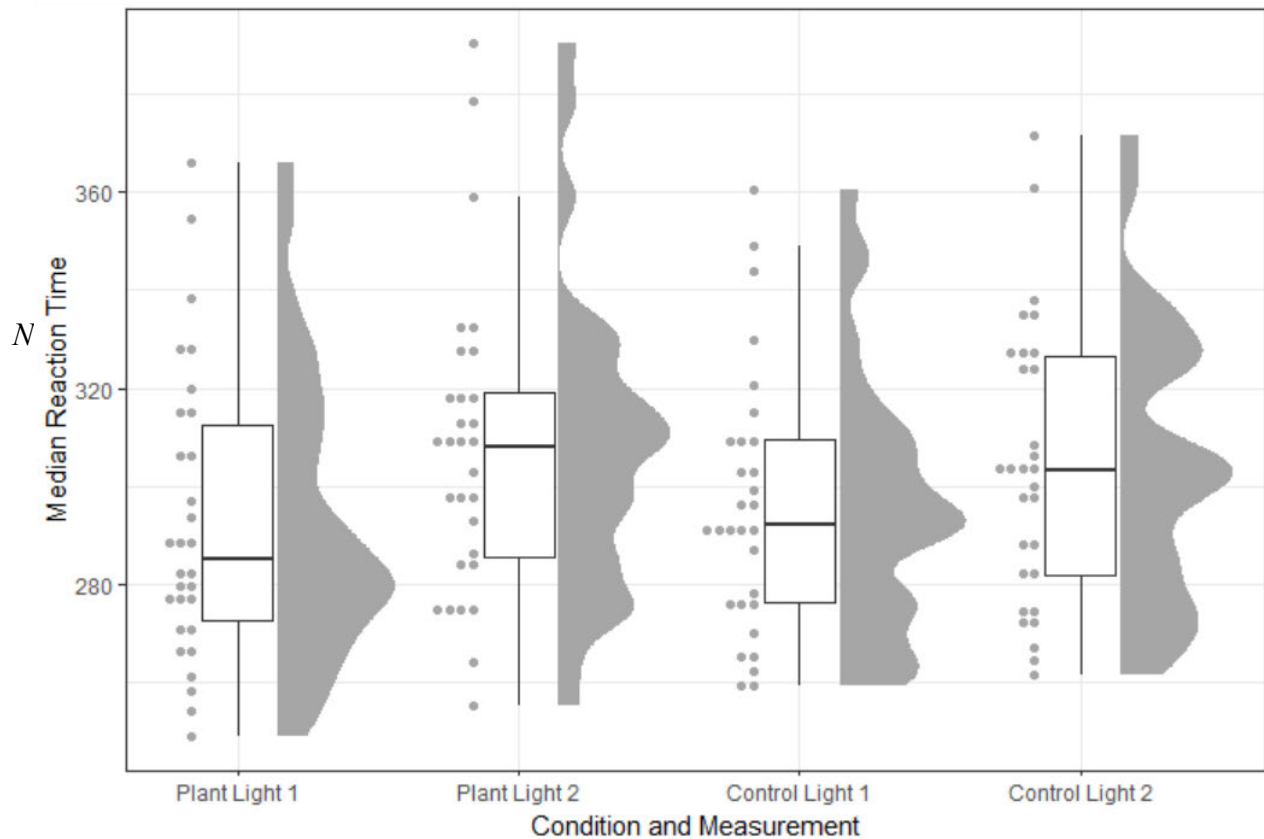
Table 4

Coefficient estimates from mixed-effects models predicting PVT outcomes

	Coefficient	Std. Error	t value	Pr(>Chisq)
Median				
Intercept	295.83	5.17	57.18	
Plant Condition	-3.05	3.87	-0.79	.900
Occasion (2)	8.22	3.87	2.13	.000*
Plant Condition:Occasion (2)	5.47	5.50	0.99	.320
Reciprocal Mean				
Intercept	0.00	0.00	54.15	
Plant Condition	0.00	0.00	0.63	.540
Occasion (2)	0.00	0.00	-2.49	.000*
Plant Condition:Occasion (2)	0.00	0.00	-0.28	.778
Lapses				
Intercept	0.77	0.21	3.59	
Plant Condition	0.07	0.25	0.26	.705
Occasion (2)	0.09	0.26	0.36	.796
Plant Condition:Occasion (2)	-0.28	0.36	-0.77	.443
False Starts				
Intercept	1.00	0.25	-1.06	
Plant Condition	0.21	0.32	0.65	.274
Occasion (2)	-0.28	0.31	-0.89	.274
Plant Condition:Occasion (2)	-0.07	0.44	-0.16	.870
Fastest 10%				
Intercept	260.77	3.71	70.33	
Plant Condition	-4.80	3.34	-1.44	.530
Occasion (2)	0.90	3.34	0.27	.074
Plant Condition:Occasion (2)	6.63	4.72	1.41	.160

Figure 3

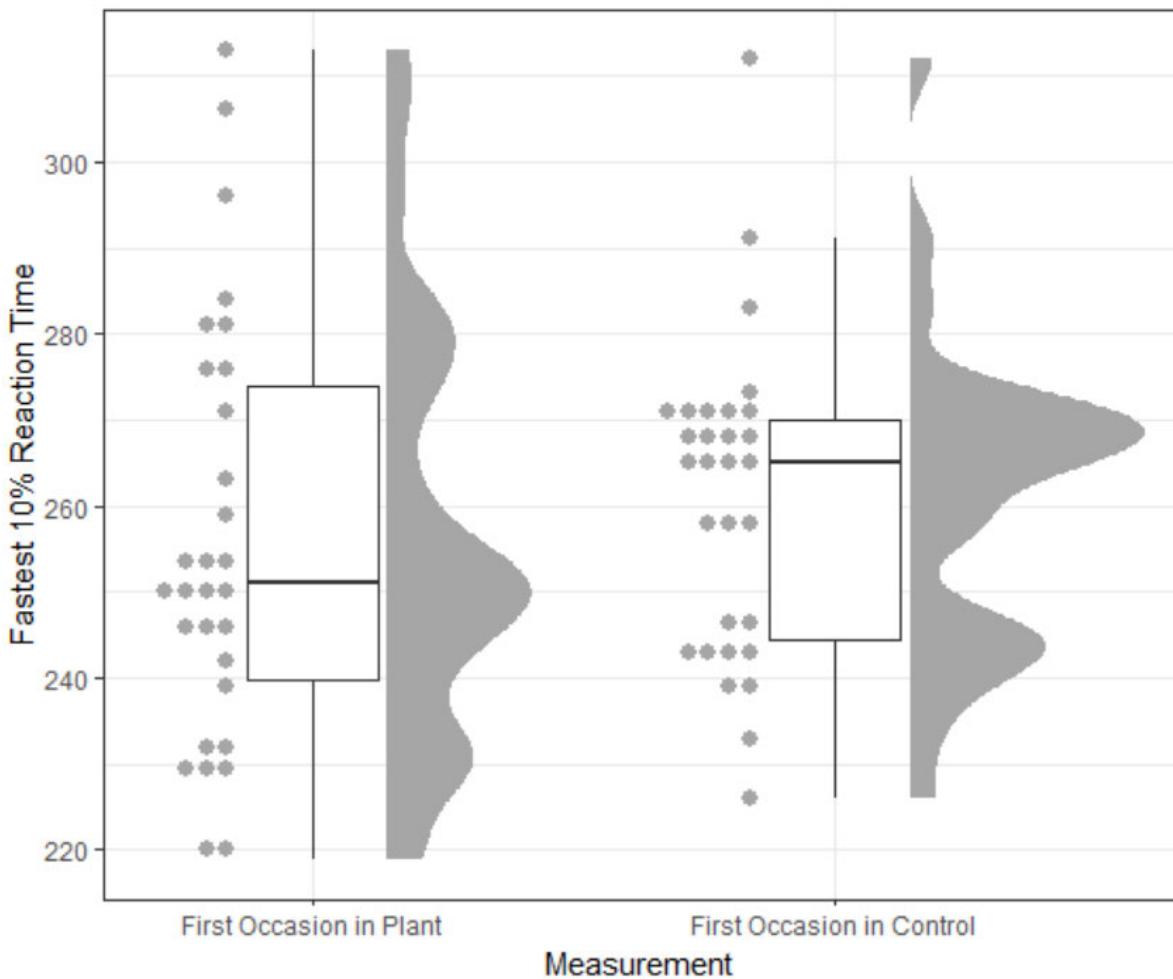
Median Reaction Time Distributions Displayed in Each Condition and Occasion



Taking a closer look at the median and fastest 10% reaction time coefficients and p values in Table 4, it appears that the main effect Plant Condition decreased reaction time by a relatively large amount, however these were not statistically significant. Interestingly, fastest 10% reaction times recorded a larger coefficient estimate when light condition was added to the main effect of occasion. After visualising the results of just the first occasion measurement in each condition, which are also evident for median response time in Figure 2, it appears there is a difference in reaction time (Figure 4).

Figure 4

Fastest 10% Reaction Time Distributions from First Occasion



To further investigate, a comparison of the two groups was conducted. First, a Shapiro Wilks was performed which indicated the distribution of fastest 10% reaction departed significantly from normality ($W = 0.98, p = 0.036$). Therefore, a paired samples Wilcoxon test was run but failed to report a significant result ($V = 804, p = 0.543$). Once again, note the

multimodal distribution and small quantity of the data as shown in Figure 4. Again, these factors indicate reduced statistical power.

Effect of Light on Cognitive Performance

A paired sampled t-test was used to test part a) of the fourth hypothesis, whether there was a significant difference in percentage of accurate responses measured during the experimental MIST condition between the plant light condition and the human light condition. First, Shapiro Wilks Tests were conducted to assess normality and was insignificant for both percentage of accurate responses in the control condition ($W = 0.95, p = .125$) and the plant condition ($W = 0.97, p = .555$). The t-test indicated that there was no significant difference ($t(29) = 0.00, p = 1.000$) between accuracy in the plant condition ($M = 53.9, SD = 10.3$) compared to the control ($M = 53.9, SD = 12.0$).

Before testing the interaction between stress condition and light condition on cognitive performance, a preliminary analysis was conducted to determine if there was a significant effect of stress condition on performance. Two Shapiro Wilks tests were conducted to assess normality and it was found that percentage of accurate responses in the control condition was significant ($W = 0.89, p = .000$), therefore, a Wilcoxon Signed Rank Test was conducted. The percentage of accurate responses from the control condition within the MIST ($M = 86.0, Mdn = 89.9, SD = 11.0$) and the experimental (stress) condition within the MIST ($M = 53.9, Mdn = 54.6, SD = 11.1$) indicate that participant percentage of accurate responses was significantly lower during the stress condition within the MIST ($t = 1830, p = .000$). Thus, further validating the stress condition as more difficult. However, a technique such as physiological imaging would be necessary to validate this condition as stress inducing.

To test the last hypothesis, whether there was a significant interaction between MIST stress condition and light condition on percentage of accurate responses a linear mixed effects model was fit. Using the same criterion method, the model of best fit included participant as a random intercept, while lighting condition, MIST condition, and MIST difficulty (one to five) were included as fixed effects and interactions. There was a significant main effect of MIST difficulty conditions within the experimental condition, as graphed in Figure 5. This helps validate MIST difficulty levels as finer grained difficulty conditions. Coefficients and p values are provided for both percentage correct and average response time per question in Table 5. There was no significant interaction between MIST stress condition, MIST difficulty, and light condition on percentage of accurate responses or response time. However, following a similar pattern to vigilance, the coefficient on the main effect of condition on response time indicated that response time decreased by an average of 32.49 milliseconds in the plant light condition compared with the control.

Figure 5

Mean and Standard Deviations of Percent Correct by Mist Difficulty Level

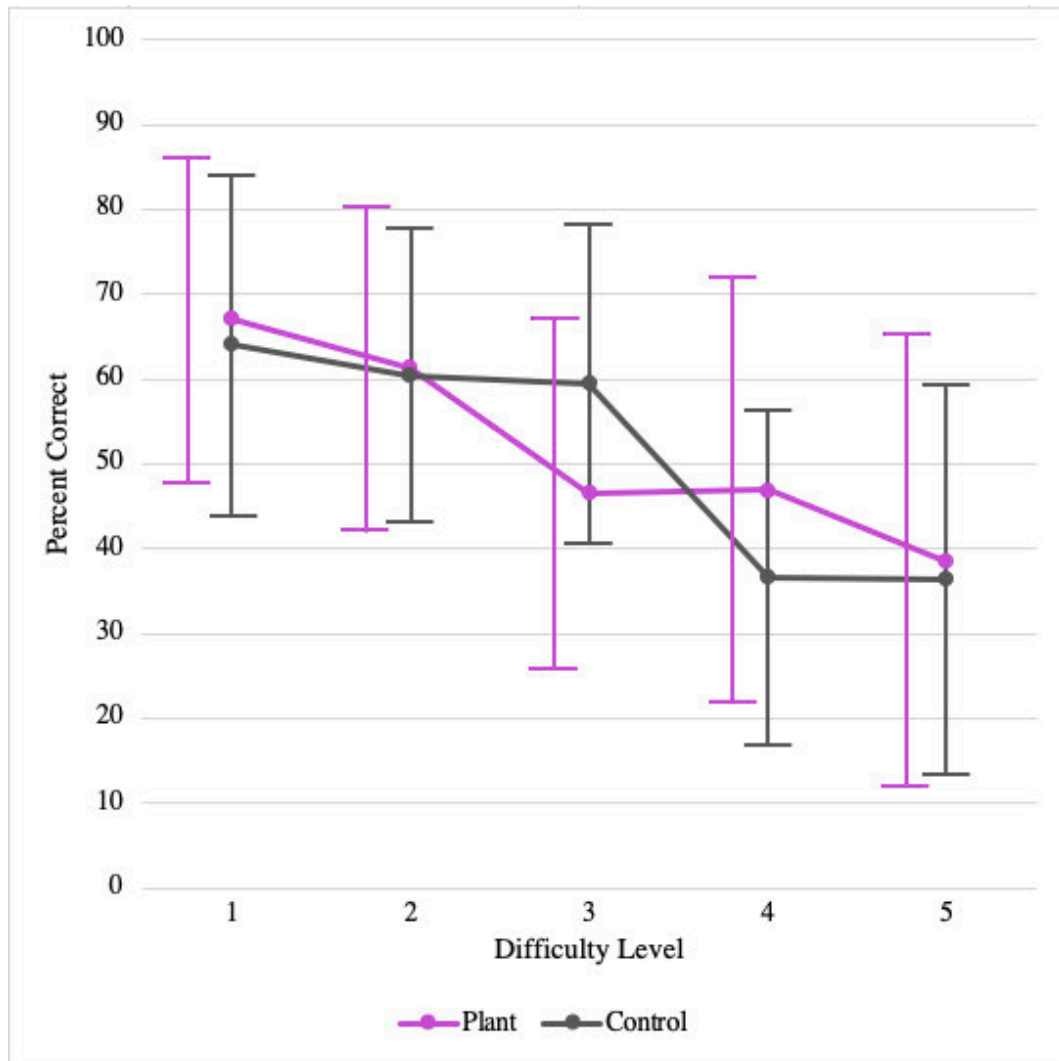


Table 5*Coefficient Estimates from Mixed-Effects Models Predicting MIST Outcomes*

	Coefficient	Std. Error	t value	Pr(>Chisq)
Percent Correct				
Intercept	98.54	4.06	24.28	
Plant Condition	-1.13	5.15	-0.22	.707
MIST Control	-34.56	5.15	-6.71	.000*
MIST Difficulty 1	-	-	-	.000*
MIST Difficulty 2	-7.22	5.19	-1.38	
MIST Difficulty 3	-16.41	5.15	-3.18	
MIST Difficulty 4	-35.81	5.15	-6.95	
MIST Difficulty 5	-34.68	5.15	-6.73	
Interaction:1	-	-	-	.087
Interaction:2	-3.66	10.28	-0.36	
Interaction:3	-22.07	10.28	-2.15	
Interaction:4	2.36	10.24	0.23	
Interaction:5	2.87	10.24	0.28	
Response Time				
Intercept	2788.73	606.38	4.60	
Plant Condition	-32.49	727.93	-0.04	.102
MIST Control	-706.00	727.93	-0.97	.000*
MIST Difficulty 1	-	-	-	.000*
MIST Difficulty 2	2771.75	727.93	3.81	
MIST Difficulty 3	5042.49	734.42	6.87	
MIST Difficulty 4	9016.66	756.52	11.92	
MIST Difficulty 5	7433.27	748.78	9.93	
Interaction:1	-	-	-	.611
Interaction:2	210.06	1452.70	0.14	
Interaction:3	202.64	1459.46	0.14	
Interaction:4	1813.60	1483.50	1.22	
Interaction:5	1584.12	1482.84	1.07	

Note. Only interactions from the full model are provided and shown in condensed form (i.e., Interaction:x = Light Condition: MIST Condition: Mist Difficulty 1-5)

Discussion

The aim of this study was to explore the effect of the light in space plant systems on emotion, vigilance, and cognition under stress. It was predicted that 1) There will be a significant effect of light condition (plant compared with human) on change in emotional affect as measured by the PANAS. 2) There will be a significant effect of light condition (plant compared with human) on change in emotional arousal as measured by the SUDS. 3) There will be a significant effect of light condition (plant compared with human) on change in: number of lapses, number of false starts, reciprocal speed ($1/RT \times 1000$), fastest 10% RT and median RT on the Psychomotor Vigilance Test. 4a) There will be a significant difference in percentage of accurate responses measured during the MIST between the plant light condition and the human light condition. 4b) There will be a significant interaction between stress condition (stress compared to control) and light condition (plant compared to human) on percentage of accurate responses measured during the MIST. In summary, although indications from descriptive statistics indicated some differences in emotion and vigilance, the effect of light modelled via linear mixed effects models and a t-test showed no statistically significant effects in differences in emotion, vigilance, and cognitive performance under stress. The theoretical and practical implications will be discussed.

Light Necessary for Plant Growth and Emotion

Measures of emotional change analysed via linear mixed effects models showed no indication of a significant effect of light. While not supporting the hypotheses, this adds to the results in the literature suggesting the effect of light on emotion is not always reliable, particularly when using subjective measures (Xiao et al., 2021). While it was not an aim of the study to compare samples under light conditions to normative data, these statistics can provide a useful comparison. Using a large Australian sample ($N = 1059$) of non-clinical Australian adults

(aged 18 to 50) it was found the average state (using the ‘moment’ timeframe) Positive Affect scores was 26.48 (SD = 8.1) and Negative Affect was 14.80 (SD = 5.49) (Heubeck & Wilkinson, 2019). Using Positive Affect as an example, mean scores at the first measurement occasion in this study was 26.3 and 25.8 in the plant and control light, respectively. Further, Negative Affect at first measurement was also within half a standard deviation of the normative sample. These mean comparisons indicate the average Affect score at first occasion measurement did not differ from normative scores. However, without running the appropriate statistics, inferences should be interpreted with caution, especially considering the flatness of variation and likeliness of underpowered statistics here.

It is possible time of exposure was a factor with the first measurement occurring directly after the five-minute PVT and approximately 10 minutes after entering the test room. Such exposure timeframes have been sensitive to changes in emotion, although acute changes are often measured using physiological mapping of emotional pathways in the brain (Vandewalle et al., 2009). Still, such evidence has informed the commercialization of bright or blue enriched bright light for treatment of mood disorders, especially for Seasonal Affective Disorder (Blume et al., 2019). However, these light therapy instruments operate at much greater illuminance levels, between 7000 and 10,000 lx and has similar therapeutic outcomes as morning sunlight (direct sunlight can record illuminance from 30,000 lx to over 100,000); compared with average vertical eye level measurements below 100 lx in the current study (Blume et al., 2019; Wirz-Justice & Terman, 2022). However, the arousing effects of light are found to begin at lux’s well below the current study, even when using subjective ratings (Cajochen, et al., 2000). Saturation is estimated to begin at estimates of approximately 100 lx (Lok et al., 2018). However, emotional valence has a more complex literature body, with often unsystematic U shaped curves at different

lux's being reported (Li et al., 2021). Thus, while it is possible the sample was not large enough to detect an effect of light spectrum with illuminance averaging below 100lx (e.g., plant condition, $M = 89.57$, $SD = 10.59$), the literature indicates emotional valence is more complex and dependent on a multitude of other factors the literature is yet to precisely define (Xiao et al., 2021).

Perhaps the largest covariate on the effect of light besides spectrum and illuminance is the time of exposure relative to the circadian cycle (Xiao et al., 2021). The results yielded some evidence for this as the Akaike information criterion favoured models which included time of assessment as a covariate. However, as described in the results, no significant differences were found in the maximal model, and it also reduced statistical power. Multicollinearity was not tested because optimal models excluded potential covariates. The literature indicates bright light and blue enriched light not only acutely effects emotion but entrains and stabilises the circadian cycle; meaning time point in this cycle is well-established modulator of mood (Blume et al., 2019; Boivin et al., 1997). Thus, it is possible light spectrum in the current study effected emotion via the longer lasting pathway of circadian governance, but this effect was not perceived by participants within the timeframe and at second occasion due to noise (as discussed in limitations). The exact mechanisms by which light interacts with emotion are currently unknown; theory in this domain still lacks large pieces of evidence (Blume et al., 2019). However, it is possible this specific wavelength induces no practical differences in emotional affect nor valence. More participants would be necessary to further understand the relationship between time of day, other potential covariates and how they interact with the effect of light necessary for plant growth on emotion.

Light Necessary for Plant Growth and Vigilance

While initial descriptive statistics showed possible small differences, the effect of light on change in vigilance as assessed via PVT outcomes was not statistically significant. This was the most surprising result according to the literature. Research has found robust evidence that supports the acute effect of blue enriched polychromatic and blue monochromatic light compared with white light on vigilance; often measured via PVTs (Siraji et al., 2021; Vetter et al., 2021; Xiao et al., 2021). While it could have been theorized that vigilance would increase due to proportion of blue light in the plant condition, the hypotheses remained non-directional due to the large amount of red light, a mix that has seemingly not been studied until now. While appearing pink or purple this coloured light has no spectral similarities to purple or violet monochromatic light which is shorter than blue (purple is approximately 400nm). An explanation for the insignificant result is the plant light (made up of blue approximately 450nm, red 700nm), may not cause significant differences in vigilance compared with polychromatic white light. In a simplified regard, it is possible the two lighting conditions are “centred” around a similar central wavelength, as white light is spectral combination of all wavelength colours. Adding the middle section of the humanly visible light spectrum, green (560nm) LED lighting condition, would provide evidence for this theory. Certainly, there is a point in the ratio between the red and blue wavelengths where the effect on vigilance would be the same as a white light of the same illuminance.

Alternatively, the blue component could still outweigh the effect of white light on vigilance. Considering the robust findings from systematic reviews on the alerting effects blue light (Siraji et al., 2021; Vetter et al., 2021; Xiao et al., 2021), together with the visible difference in median reaction time and top 10% of reaction times at the first occasion, this theory should be

vigilantly considered. Further explanation of this theory is discussed in the in the general limitations of the study.

Light Necessary for Plant Growth on Cognition and Stress

The results did not support the hypotheses that there will be a significant difference in cognitive performance and cognitive performance under the stress condition induced via the MIST between light conditions. However, like some outcomes of vigilance, coefficients indicated average response times were faster in the plant light condition. As a more complex psychological measure (like emotional valence), the effects of blue light have been found to effect higher cognitive function but shares large covariance with other factors such as task complexity, time of assessment, and control light properties (Siraji et al., 2021; Xiao et al., 2021; Münch & Bromundt, 2022). According to the literature, it is likely that response time had a lower, albeit insignificant p-value, because it is a simpler measure of cognitive performance. Time of day may also explain these contradictory results to the literature, although substantial evidence has been collated to demonstrate the acute effect (on both vigilance and cognition) of blue light even at night-time (Cajochen, 2007). This study helps to clarify this important nuance between the interaction of time of day on simple cognition compared with emotion.

Like vigilance and emotion, light can affect cognition via the synchronizing or phase-shifting pathway regarding the circadian cycle but has also been shown to acutely affect cognition within minutes (Vandewalle et al., 2009). Thus, there are likely other explanations for the current study's lack of significant findings. As these relate to all dependent variables of interest, these general limitations will now be discussed.

Limitations and Recommendations

The first major limitation was failing to recruit the minimum sample size of 50 participants which reduced the statistical power by a substantial amount (Baker et al., 2021). Out of the 30 participants that were included in final analyses there were varying degrees of English comprehension level. This is particularly limiting for the emotional effect measures which were psychometrics designed and validated using English speaking Western samples. While participants were all screened for a 'good level of English comprehension' they were not screened for cultural differences which create variance in outcomes and cause more divergent results on measures of affect compared to measures of simple or arithmetic cognitive performance (An et al., 2017). Gaining larger samples and recording first language as a potential covariate or collecting culturally homogeneous samples would increase reliability and statistical power.

As previously highlighted, a large covarying factor in the non-image forming effects of light is time of day or more precisely, circadian timing (Siraji et al., 2021). Initially the study aimed to measure all participants at the same time of day in the mid-morning, however, equipment setbacks which created a large time constraint making this impossible. The current study's data collection continued until less than three weeks before the full study needed to be finished. Future research should aim to measure the effect of light on emotion at the same time of day. Although future research which aims to measure emotional affect should recruit a large enough sample to include this as a categorical variable with sufficient power to detect small effects. The latter is also recommended to provide evidence which can construct a more complete theoretical model about all outcomes.

An important limitation which can help to provide explanation of the current study in relation to the literature body is the extensive cognitive assessments and repeated measures

would have produced effects such as fatigue, adaptation and learning effects. The counterbalanced within subject's design provided a greater amount of statistical power compared to a between subject's design of the same sized sample (Baker et al., 2021). However, future researchers should be cautious when using cognitive tasks which have semi-blinded elements such as the stress condition in the MIST as learning or adaptation effects can decrease the chance of detecting an effect, especially with smaller sample sizes (Baker et al., 2021). As recommended by the MIST developers, research should ensure participants are not aware of how the MIST is specifically designed to induce mild evaluative stress (Dedovic et al 2005), although due to the necessary transparency of informed consent, participants could have searched for this information. It is possible that all outcome measures were affected human adaptation to the light, fatigue, or in the case of the PVT, SUDS, and PANAS, residual stress from the MIST. This may help to explain why coefficients and visual analyses seemed to identify the largest differences only on the first occasion. For the importance of visual adaptation in this domain of research it is relatively understated in theory (Clifford, et al., 2007). When studies investigate the emotional and cognitive effects of visual stimuli over long periods of time, these studies are also implicitly or explicitly investigating the efficacy of the human adaptive process. This was explicitly studied in the current research via the different stress conditions within the MIST and the repeated PVT, PANAS, and SUDS measures within one light condition. Therefore, while the study was limited regarding statistical power, it provides preliminary results on the adaptive processes relevant to visual stimuli. In this regard, this is not statistical noise, it is a valid element that should remain in future designs which aim to understand the full effect of stimulus on important populations such as crew members who interact with space plant systems. However, there are some

important considerations that will be discussed, besides ensuring statistical power is sufficient to detect effects during long assessment batteries which include repeated measures.

Initially, the study aimed to use either EEG or a wearable to device to measure either brain activity or heart rate metrics, respectively. However, due to further equipment delays and difficulties, triangulation of the measures of emotion and cognition with physiological measures was not possible. It is highly recommended that future studies include these measures, not only does this help triangulate effects to full psychophysiological models of effect but have often yielded more reliable and informative results in prior research (Askaripoor et al., 2019; Badia et al., 1991; Bruce et al., 2003; Okamoto et al., 2014). Employing this measure, designs could change light qualities during assessment or participants could move from condition from condition relatively quickly. If the acute responses are of primary interest, this would mitigate any adaptation effects towards light. Or if a more face validity is preferred this may be an option as Poulet et al (2021) state crew members are only exposed to the plant light for minutes at a time (although this time would increase as space plant systems become larger).

The study aimed to collaborate with other disciplines to create an analogue model of the interior of the ISS with a full working space plant system. However, delays on this project moved assessment into a generic laboratory setting. To increase the validity of the assessment conditions this is highly recommended. As reviewed, crew members are subject to a myriad of adverse factors (e.g., subject to confined space, lack of natural elements) which negatively affects their ability to adapt to varying stimuli (Pagel & Choukèr, 2016; Gushchin et al., 2019; Odeh & Guy, 2017). This is a greater consideration if research investigates the human response to plants, as plants are theoretically a mitigating factor of the adverse conditions specific to human space settings (Perchonok et al., 2012; Massa et al., 2016; Neilson et al., 2021). Including

this element by creating control conditions where plants are simply absent from the lighting condition is recommended for future research granted adequate samples can be recruited. This inclusion would make it possible to quantify the current findings while recording preliminary results for the effect of plants on human outcomes in space plant systems.

Another consideration for future research is pairing the important light characteristics (i.e.,) with what is commonly used in space plant systems (get it right ref). Due to the nature of the pilot study and the lack of technological resources, this study could not precisely describe the light characteristics observed by participants, according to recommendations (Knoop et al., 2019; Spitschan et al., 2019). Specifically, quantifying the exact spectral qualities or matching light via measurement to a system like Veggie limited the generalizability of the results. However, the light was set to a specialized plant setting, which is visually identical to that of 'Veggie'. Veggie has a ratio of four to one (red to blue, respectively) on each plant growth settings (low, medium, and high). While appearing pink or purple this coloured light has no spectral similarities to purple or violet monochromatic light which is shorter than blue (approximately 400nm). This light, containing the two ends of the spectrum (blue approximately 450nm, red 700nm), may not cause significant differences in vigilance compared with polychromatic white light. In this regard, it is possible the two lighting conditions are "centred" around a similar central wavelength, as white light is just a spectral combination of all wavelength colours.

While some participants were omitted for disregard of instructions, phone use was not included in the informed consent and information sheet. It is recommended this should be included or there should be a way of monitoring the full general participant behaviour (e.g., running one participant at a time and remaining present or some sort of monitoring window or system).

The computer screen also complicated light stimuli in the test room. Especially since modern computer screens have been found to affect a wide range of human responses, including outcomes measured in the current study (Brown et al., 2022; Small et al., 2022). While this study dimmed and standardised the computer screen, it is possible the light had unforeseen effects, such contrast between the white computer screen and purple look in the plant condition. This may have contributed to decreased scores on PVT responses in this condition. It is recommended that measurements are recorded without added light stimulus where possible. Physiological measures such as EEG can provide robust data in the field without necessarily including the computer screen (Askaripoor et al., 2019; Badia et al., 1991; Okamoto et al., 2014).

Conclusion

The research provided preliminary results regarding the effect of light deemed necessary for indoor plant growth on human emotion, vigilance, cognition, and cognition under stress. While the generalisability of results was limited due to practical setbacks constraining time and sample size, the study still revealed important recommendations for future research. The key strength of the study was providing preliminary results for the research context, regarding the use of an extensive list of theoretically and empirically valid measures. Funding research related to space is relatively expensive and highly debated. However, the discoveries and advancements in this domain have been vital for the improvement of human health and wellbeing on Earth. Every day individuals benefit from technologies and research transferred from space domains. A small list of examples of the benefits include practical applications such as LED lighting, wireless headsets, freeze-dried foods, memory foam and scratch-resistant eyeglass lenses. Medical advancements include fibre optic catheters, artificial limbs, and voice-controlled wheelchairs. Public safety mechanisms include firefighting equipment and landmine removal (Chung et al.,

2010; Clifford et al., 2007). The American Psychological Association mission statement is to ‘...to promote the advancement, communication, and application of psychological science and knowledge to benefit society and improve lives’ (APA, 2022). In light of this, the study was a useful step to understanding how plant space systems effect crew members and how these systems will be developed to positively impact upon human performance, health and wellbeing. When considering the distances, time requirements and foreign environmental settings required to travel to Mars, and beyond, finding opportunities to improve the human condition of those taking the journey will be inextricably linked to the success of such missions. And back on Earth, it further adds to the growing body of literature which aims to understand the effects of LED light, a relatively new and under researched stimuli, which will continue to effect billions of people each day.

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Appendix A

Assessment Script

After consent form is signed. Thank you, now if you could please sit down in this room and make sure you're comfortable. *Shut door and note time – this instruction block will also help adjust the participant to the lighting, testing should only start after at least 5 minutes under the light. Shut door. Measure light.* When testing starts you will be asked to complete a series of tests on the computer and via paper. Instructions for the computer tests will appear on the screen and instructions for the paper questionnaires are included on the sheet, please read and follow them carefully. I'll give you time to read each set of instructions while I'm present in case you have any questions, but please only begin the test or questionnaire once I have left and shut the door.

To ensure correct ordering, when you finish the first task, please knock quietly on the door to let me know and I will direct you to your second task. Please repeat this process upon completion of each test. If I don't answer the knock straight away, please wait around a minute before lightly knocking again as I may be busy with another participant. If you are unclear about any of the instructions at any time please let me know. If you need to take a break or wish to discontinue participation at any time, you do not have to knock or wait to do so, please just let me know. Do you have any questions?

I will now set up the first test on the computer.

Set up the Psychomotor Vigilance Test. Please read the instructions carefully. *After read instructions.* Any questions? *If 5 minutes hasn't elapse. If 5 minutes has elapsed.* Good, I will now leave the room, after which you can start.

PVT

After knock, open door. Any problems with that one? *If yes, note problem type and participant ID.* Alright, thanks.

Now could you please complete sheet number one. *Hand them the first PANAS.* Followed by sheet number two. *Hand them the first SUDS.* Please knock after you have completed both in that order. *Leave room and shut door.*

PANAS1 AND SUDS1

After knock, open door. Any problems with those? *If yes, note problem type, measure and participant ID.* Alright, thanks.

Now I'll set up your next test on the computer. This test is designed to stress you out a little, please remember

As you will read, this task requires the left, right and middle button of the mouse. To use the middle button with this mouse, you will instead need to lightly tap using three fingers, it is as

sensitive as a phone screen, so you don't need to apply any pressure. Careful not to left or right click at the same time as this may submit an answer you didn't want. I also find it more reliable to move my fingers down to about halfway as I'm less likely to accidentally click. So, this is a right click, this is a left click and this is a middle tap. *Demonstrate.*

Set up the Montreal Stress Imaging Task. For this one there are different conditions, please knock and I'll let myself in before you begin the "test" condition. A screen will appear that looks like this. *Show screenshot.* Please begin once you've read the instructions carefully and remember to knock and wait for me when you see the test condition screen. *Leave room.*

Before experimental (test) condition begins. So, during this section you must answer the questions correctly, and if you don't perform as well as the others in the study then your data won't be used. Prior participants answered more than 80% of the answers correctly, so if you don't answer at least 80% correct your data won't be used. *During the experimental condition, two minutes after they have answered the first question* "You are not answering enough of these correctly. Please try as hard as you can to get these right."

MIST

Any problems with that one? *If yes (outside of expected MIST difficulties), note problem type and participant ID.* Alright, thanks.

I will now set up your next computer test.

Set up the second Psychomotor Vigilance Test. Please begin once you have read the instructions carefully and I've shut the door. *Leave room and shut door.*

PVT2 – on the last they can do both

After knock, open door. Any problems with that one? *If yes, note problem type and participant ID.* Alright, thanks.

Now could you please complete sheet number three. *Hand them the second PANAS.* Followed by sheet number four. *Hand them the second SUDS.* Please knock after you have completed both in that order. *Leave room and shut door.*

PANAS2 AND SUDS2

After knock, open door. Any problems with those? *If yes, note problem type, measure and participant ID.* Alright, thanks.

END OF CONDITION ONE.

I will now give you around a 5-minute break before the second round of testing. *Rest session should include 5 minutes under the second lighting condition.* If you could please sit down in this room and make sure you're comfortable. Once again, I will read the instructions, just to ensure the two conditions are as controlled as possible.

When testing starts you will be asked to complete a series of tests on the computer and via paper. Instructions for the computer tests will appear on the screen and instructions for the paper questionnaires are included on the sheet, please read and follow them carefully. I'll give you time to read each set of instructions while I'm present in case you have any questions, but please only begin the test or questionnaire once I have left and shut the door.

To ensure correct ordering, when you finish this first task, please knock quietly on the door to let me know and I will direct you to your second task. Please repeat this process upon completion of each test. If I don't answer the knock straight away, please wait around a minute before lightly knocking again as I may be busy with another participant. If you are unclear about any of the instructions at any time please let me know. If you need to take a break or wish to discontinue participation at any time, you do not have to knock or wait to do so, please just let me know. Do you have any questions?

I will now set up the first test on the computer.

Set up the Psychomotor Vigilance Test. Please read the instructions carefully. After read instructions. Any questions? If 5 minutes has elapsed. Good, I will now leave the room, after which you can start.

PVT

After knock, open door. Any problems with that one? If yes, note problem type and participant ID. Alright, thanks.

Now could you please complete sheet number one. *Hand them the first PANAS.* Followed by sheet number two. *Hand them the first SUDS.* Please knock after you have completed both in that order. *Leave room and shut door.*

PANASI AND SUDSI

After knock, open door. Any problems with those? If yes, note problem type, measure and participant ID. Alright, thanks.

Now I'll set up your next test on the computer.

As you will read, this task requires the left, right and middle button of the mouse. To use the middle button with this mouse, you will instead need to lightly tap using three fingers, it is as sensitive as a phone screen, so you don't need to apply any pressure. Careful not to left or right click at the same time as this may submit an answer you didn't want. I also find it more reliable to move my fingers down to about halfway as I'm less likely to accidentally click. So, this is a right click, this is a left click and this is a middle tap. *Demonstrate.*

Set up the Montreal Stress Imaging Task. For this one there are different conditions, please knock and I'll let myself in before you begin the "test" condition. A screen will appear that looks

like this. *Show screenshot*. Please begin once you've read the instructions carefully and remember to knock and wait for me when you see the test condition screen. *Leave room*.

Before experimental (test) condition begins. So, during this section you must answer the questions correctly, and if you don't perform as well as the others in the study then your data won't be used. Prior participants answered more than 80% of the answers correctly, so if you don't answer at least 80% correct your data won't be used. *During the experimental condition, two minutes after they have answered the first question* "You are not doing as well as we had hoped. Please do your best to answer these correctly."

MIST

Any problems with that one? *If yes (outside of expected MIST difficulties), note problem type and participant ID*. Alright, thanks.

Now could you please complete sheet number three. *Hand them the second PANAS*. Followed by sheet number four. *Hand them the second SUDS*. Please knock after you have completed both in that order. *Leave room and shut door*.

PANAS2 AND SUDS2

After knock, open door. Any problems with those? *If yes, note problem type, measure and participant ID*. Alright, thanks.

I will now set up your next computer test.

Set up the second Psychomotor Vigilance Test. Please begin once you have read the instructions carefully and I've shut the door. *Leave room and shut door*.

PVT2

After knock, open door. Any problems with that one? *If yes, note problem type and participant ID*. Alright, thanks.

END OF ASSESSMENT

Appendix B

Figure 1

Title

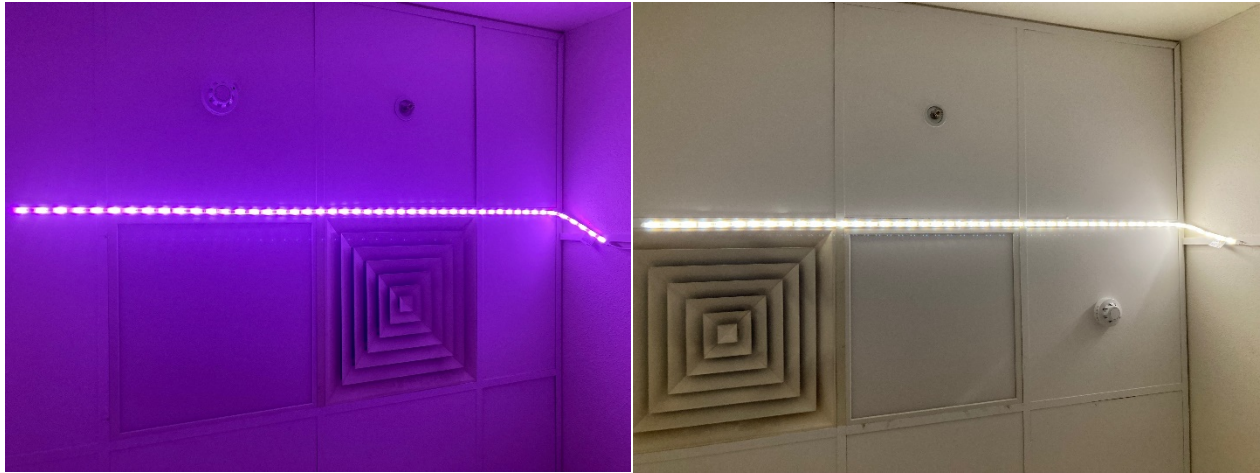


Figure 2

Title

