The effect of working memory on word stress placement and processing

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Abstract

Investigating the role of word stress has been prevalent in linguistics literature, but not from a cognitive perspective. One way of understanding the underlying cognitive mechanisms used when assigning word stress is through the use of computational models of reading. An important difference between these models exists in whether they assume stress is imputed serially from left to right or whether they assume all aspects of a word are processed together (i.e. in parallel). We tested this prediction by examining the effect working memory load had on stress assignment in words and nonwords. If processing is serial, then current computational models predict that, in high versus low memory load conditions, a greater proportion of responses should start with a trochaic compared to iambic feet, and that processing speed should be slowed more for words that start with iambic compared to trochaic feet. The results from a stress judgement task examining this showed that, in a high compared to low memory load condition, participants gave significantly more trochaic responses to both words and nonwords and that reaction times were slowed more with words starting with iambic compared to trochaic feet. These results support models of stress assignment that are serial and occur from left to right.

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 the 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.

Contribution Statement

In completing my thesis, my supervisor provided the research question of interest, formulated the methodology, provided the program used for data collection as well as the code used to conduct the analysis. I conducted the literature search, completed the ethics application, recruited all participants and completed data collection. I performed the analysis and interpreted the output. Finally, I wrote up all aspects of the thesis.

The effect of working memory on word stress placement and processing

What is Word Stress?

Word stress can be simply defined as prominence given to a syllable in a word (Lin, Wang, Newman, & Li, 2016) and is an integral part of language acquisition (Honbolygo, Kober & Csepe, 2019). For example, with the word ambience, the first syllable (the **am** in ambience) has more prominence than the second and third. Stress[1] can also help us access the form and meaning of a word (Perry, 2017). Getting stress wrong can cause words to be difficult to identify (e.g. win**dow** instead of **win**dow) (Sulpizio, Burani & Colombo 2015), or cause incorrect identification through altered meanings (e.g. **For**bear vs For**bear**) (Lin et al, 2016).

Linguistics Perspective

What word stress is and its role has been the subject of much discussion in the linguistics literature (e.g. Chomsky & Halle, 1968), covering many different languages (Goedemans & van der Hulst, 2014). Languages use word stress differently, but it is commonly used to help differentiate the meaning of words as well as synchronise the timing of the language (Honbolygo et al, 2019).

There are a number of ways stress can be assigned to words. In the simplest case, stress can occur either a certain number of syllables from the beginning of the word (rightward assignment) or a certain number of syllables from the end of the word (leftward assignment). In some languages, the same pattern occurs on essentially all words, and thus they have a fixed pattern. For example, Hungarian always has first syllable stress (Goedemans & van der Hulst, 2014). Alternatively, many languages have much more variable stress assignment, where the

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[1] We will refer to word stress as stress in this thesis

assignment of stress is somewhat predictable, but there is no simple pattern that can be applied to all or even most words (Heisterueber, Klein, Willmes, Heim & Domahs, 2014). English is a good example of this (Fudge, 1984; Arciuli & Monaghan, 2010), where regularities exist, but they are never all-or-nothing. For example, most bisyllabic nouns in English have trochaic stress (i.e., stress on the first but not second syllable, e.g., **cur**tain, **arm**pit, **car**bon). However, there are many exceptions which have iambic stress (i.e. stress on the second syllable instead of the first e.g., ba**lloon**, re**mark**).

Cognitive Approach?

The underlying cognitive processes involved in how stress is assigned to words have received far less attention than in linguistics analyses. Even less attention has been given to how people generate stress from writing even though there are many cues in orthographies that help us predict stress (Arciuli & Cupples, 2006). In addition, most of this literature has looked at where stress is assigned based on orthographic regularities – that is, statistical regularities found in languages, and not the underlying processes or demands associated with applying stress. The general conclusion is that that, unsurprisingly, people are sensitive to statistical regularities in stress, and thus the underlying cognitive system must use more than just a simple set of rules. However, what that system might be has not be well elucidated.

The Working Memory

One way of investigating the cognitive processes that underly stress usage is to look at the effect of phonological working memory (which we will refer to simply as working memory in this thesis) on how stress is assigned. Working memory is a limited capacity for temporary storage and manipulation of information for complex tasks (Baddeley & Hitch, 1974), including speech. The impact of working memory has been documented in general language processing and supports a wide range of linguistic behaviours, such as word learning and reading skills (e.g. Perrachione, Satrajit, Ostrovskaya, Gabrieli & Kovelman, 2017). It is also known to be important in reading (Nouwens, Margriet & Verhoeven, 2017) and stress assignment (Domahs Grande, Huber & Domahs, 2014). Domahs et al. (2014) investigated this and found that indeed working memory had a role, particularly those under a high working memory load had less diverse stress placement than those in the low condition.

Serial Processing versus Parallel Processing

An important aspect of reading that may affect the processing of speech is how phonology (sound) is generated. Different models make different predictions. The CDP (Perry, Ziegler & Zorzi, 2007, 2010) and DRC (Rastle & Coltheart, 1995) models predict that phonology is in part generated using a mechanism that breaks letters into groups and imputes their sounds in a left-to-right serial fashion. Other models assume that all letters are always processed in parallel (i.e., at the same time; e.g., Plaut, McCelland, Seidenberg & Patterson, 1996).

Models such as the Dual route model of reading (DRC) and the CDP++ both demonstrate that assigning stress and language production is done using two procedures. One is a simple memory lookup, where words that are learnt can be recognized in parallel from their letters. However, they both also have a mechanism that can impute the phonology of words, which is useful for novel words. There is also very good evidence that this mechanism operates and competes with the simple memory look-up even in normal reading (Perry et al, 2010). It works by incrementally, going from left to right on a letter string, starting from the beginning. The assumption is that information is processed in a cascaded fashion where as soon as parts of words are processed, these parts becomes available to different parts of the system. This means that the left part of words is available earlier than information on the right (Rastle & Coltheart, 1995). More specifically, with the CDP++ model, letters are grouped into graphemes of one or more letters (i.e., groups of letters which typically map to single phonemes, e.g., the ‘ch’ in ‘chalk’). That is, they are *parsed*. As this occurs, they are placed into a syllabic template that organises them. From this template, phonology is then generated. This is done incrementally, so as soon as the grapheme is parsed, phonology can be generated, and phonology generated from smaller numbers of graphemes can potentially be updated. (Perry, 2017).

Given some models of reading have a process which operates serially, it is possible to make predictions about the effect of stress based on this. In particular, even though English has a variable stress pattern, stress is statistically more likely to fall on the first syllable than any other (Arciuli & Cupples, 2006). This bias towards initial stress can be seen in practice in other languages as well. In one study (Schiller, Jansma, Peters & Levelt, 2006)., Dutch participants were quicker to detect syllables at the beginning of a word, rather than the end, after naming form pictures. The authors concluded this was because Dutch words typically have stress on the first syllable.

Thus, when the smaller parts of the words are placed into the graphemic buffer (to receive phonology), the phonology they produce will tend to favour first syllable stress. Because of the parsing mechanism, the earlier information becomes available, the more likely it is to affect reading simply because it has longer to be processed before the latter letters are encountered. This could help or hurt the correct retrieval of stress in some circumstances. For example, if a word like carbonless is processed from left-to-right, then the information is always correct (**car** – first syllable stress, **car**bon – first syllable stress, **car**bonless – first syllable stress). Alternatively, if a word like carbonic is processed from left to right, then the bias can hurt the correct assignment of stress (**car** – first syllable stress, **car**bon – first syllable stress, car**bon**ic – second syllable stress).

Whilst the predictions of serial models are clear, there are other models suggesting that reading words is done in parallel. In this respect, the 'Triangle' model of Plaut et al. (1996) assumes that processing happens in parallel across a set of letter and phoneme units. In the context of word stress, all letters are processed at once, and so the rightmost letter is thus processed at the same time as the leftmost and indeed all other letters. Stress is also generated as soon as the word is presented (Seva, Arciuli & Monaghan, 2009). Thus, it could be said that people plan their entire utterance in advance, rather than incrementally deciphering the word one syllable at a time. This is in contrast to serial models, in which syllables are processed in smaller incremental units with no planning in advance (Melinger, Branigan & Pickering, 2014). This model predicts that, in English, first syllable stress is preferred as it is simply a reflection of the lexico-statistics of the language, and that the type of computational problems that might be caused by words with atypical stress when processed in a serial fashion (c.f., carbon, carbonless, and carbonic) should not exist.

Memory load: Speed of Processing

The impact of memory load is another aspect that could have an impact on stress processing (Domahs et al, 2014).

One effect that working memory load may have is slower processing. This is particularly important if processing occurs serially, because it could cause a serial process to slow down and effect processing dynamics in a way that a parallel process would not be affected. In particular, if memory load slows the speed of serial processing, this would mean later parts of a letter string would be processed even later than otherwise be the case. In some situations, such as when a final morpheme affects stress, this would mean it would a longer amount of time to generate the correct stress. This is perhaps easiest to understand from an example using a morpheme like ***car****bon*, which typically has first syllable stress and how this compares to car**bon**ic, which has second syllable stress. With the second of these words, it would take time to get to the end of the word which would then allow the correct stress to be inferred. In particular, if the word is slowly revealed to you, it is not until the end of the word that you can infer the correct stress. For example, **car** -> **car**bon is correct, but when you reach car**bon**ic, the appearance of the final morpheme (-ic) alters the stress pattern (the -ic morpheme almost always causes stress to fall on the syllable that occurred before it). This means that it would be slower to process a word like *carbonic* compared to *carbonless* because it is not until the end of a word that it is possible to impute stress correctly, and this will take time to get to because it is at the end of the word. With a high working memory load, this problem may be exacerbated because incremental processing would be slowed down, so getting to the end of the word and hence generating the correct stress would take a longer amount of time and requires more effort to resolve.

Compared to a serial stress assignment, a parallel stress assignment makes different predictions. This means that in a word like carbonic, unlike if a word was processed serially, the final morpheme -ic would be processed immediately, allowing for correct stress to be inferred without the amount of interference the first two syllables would cause if processing was serial. In this case, the -ic is a very high frequency cue and is also very consistent in terms of it causing stress to fall one syllable before it. It would thus be likely to reduce any differences caused by the potential inconsistency of the first two syllables, especially because current parallel models assume non-linear relationships can be learnt. This means that if there is a relationship that is regular and of frequency, like -ic, it would be learnt over and above other statistical regularities (see Plaut et al., 1996). A parallel model therefore predicts that even with a higher working memory load, being able to process all aspects of a word at once means that the processing costs of generating stress should not be severely affected.

Memory Capacity and Cues

Another aspect of memory load that could affect processing is that it could affect where stress is placed. Cues (statistical or orthographic regularity) can offer contextual elements to aid in the potential stress pattern of a word. Parallel models such as Seva et al, uses these statistical regularities in its training to map orthographic input onto stress patterns. Therefore, it can learn very complex patterns between orthography and phonology (Ktori, Petroula & Rastle, 2018). In the previous carbonic example, words with -ic as the final syllable will almost always have penultimate (second) syllable stress in the word (Perry, 2017). The utilisation of such concrete cues could also possibly relate to the underlying cognitive processes of stress placement.

It has been shown that readers are sensitive to such cues and Behavioural data has shown that the ability to use reliable indicators of cues to parse stress had more accurate outcomes than those that were not reliable (Kelly et al, 1998). Other examples of orthographic cues that carry reliable information about stress position is -be (unstressed at the beginning) and -een (stressed at the end) (Seva et al, 2009).

How memory load could affect processing is that those possessing a larger capacity may have the ability to take advantage of cues across multiple elements of a word, compared to those with a lower working memory capacity. Being able to process the entire word at once can allow one to take full advantage of a cue, this is especially important for a cue like -ic as noted before. In addition, word endings have been seen to have more influence on correct stress placement than beginnings (Arciluli & Cupples, 2006). It can potentially lead to correct stress placement without being affected much by cognitive demands. If one’s memory capacity was so poor that they could only process a single syllable at once, depending on where stress falls, these contextual cues may disappear. This effect was somewhat already demonstrated by Kriukova & Mani (2016). Trochaic words that have a privileged processing status (first syllable stress) reduced the contextual effects, in comparison to iambic words (second syllable stress), where an effect was found.

A study by Kelly, Morris & Verreikia. (1998) demonstrated that in a lexical decision task. Participants reaction times and error rates were both significantly shorter for when the syllable were reliable indicators of stress, compared to those that were not. Thus, being able to take advantage cues, it could also be predicted that those with a higher working memory capacity are most likely not going to be adversely affected by additional working memory costs and thus processing should only be slightly slower.

Previous Studies

Few studies have explicitly investigated the impact of working memory processing on word stress. However, it is well known from other areas of language that cognitive load does tend to affect performance. For example, in a study related to sentence planning and tasks demands, an increase in cognitive demand (remembering numbers) caused less planning and more incrementally produced outcomes – that is the incremental steps needed in semantic planning were slowed down. Less planning occurred to allow for participants to cope with the extra demand (Wagner, Jescheniak & Schreifers, 2010). Similarly, the impact of working memory capacity can also be seen in the prosodic analysis of sentences. Those with higher capacity are able to chunk the entire sentence and treat it as a cohesive unit. On the other hand, those with lower capacity, could only process one section at a time (Swets, Desmet, Hambrick & Ferrerira, 2007).

The most comprehensive so far is a study investigating individual working memory on word stress in German. They found that German most likely uses leftward stress, starting at the end according to this pattern: Final Syllable <- Second Syllable <- First Syllable. Unsurprisingly, those who had a limited working memory, avoiding starting stress on the final syllable. This was simply it was distant from the starting point, thus most placed stress on the first syllable because it was computationally easier for them. Most notably, however, it was found that there was significant positive correlation between Working memory capacity and the proportion of first syllable stress assigned in non-words. That is, those with higher working memory capacity more often than not assigned stressed to the first syllable, in comparison to the last. There was also no correlation between Working memory and second syllable stress, this is quite surprising because in German, second syllable stress is considered “default”. In addition, it is also of interest that many would start from the end of the word, as leftward processing can be seen as more demanding than rightward stress (starting from the beginning). Participants starting at final syllable stress would first process the prior two syllables in order to identify stress positions. They found that those possessing higher working memory load had more diverse processing procedures, that is, they could start processing from the final syllable (the most demanding) but were not restricted to this pattern. They found that the reason for some avoiding second syllable stress is that there may actually be an articulatory advantage for stress patterns starting from the end (like Italian). Words stressed on the first syllable are faster than those on the second (Domahs, 2014). Useful implications can be gleaned from this study, but perhaps the effect of cognitive load on participants with poor results could be related to the age of participants (Mean age = 71) as opposed to the additional working memory task they had completed.

A number of useful things can be gleaned from this study in relation to our predictions. Those with better working capacity are able process to the entire word at once, correctly choosing stress in a variety of position, without just defaulting to the first. Additionally, for those with limited memory capacity, participants move away from processing methods that involve cues and rely on default stress. This use of first syllable stress implies that stress is processed in serial, starting from the beginning.

This Study

This study tests the predictions derived from both models and explores the effects of working memory on the processing and placement of word stress. This study has two aims. The first is to investigate the extent to which stress is applied left or right, that is, is it processed in serial or parallel. The second will be to investigate the impact of working memory load on stress assignment. Will a greater cognitive load cause more participants to default to first syllable stress (and thus support serial processing)?

To pursue these aims, the task completed will be a simple stress recognition task, where participants are asked to indicate whether a word or a nonsense word (I.e., something that could be a word but is not, e.g., slorpul) has first or second syllable stress. First and second syllable stress is significant as previous studies demonstrate that stress is processed differently depending on whether stress falls on the first or second syllable. Working memory capacity was measured with an additional task that participants had to do alongside the stress task.

The words used in the exercise will be a combination of mostly trisyllabic words that are stress ambiguous (stressed on first or second syllable) and non-words (words that do not have a pre-determined stress pattern). In addition, words may also be either stress regular or stress irregular. It is also of interest, particularly with non-words, to see what participants choose and whether or not they default to the first syllable.

If stress is processed in a serial manner, we should therefore see a gravitation towards first syllable stress, regardless of words or non-words, this should be especially noticeable in the higher working memory load. We should expect a bias towards first syllable stress as both the CDP++ and parallel models predict that there is a processing advantage for initial stress. It is suggested that this is because both models were trained on words that featured more first syllable stress than second. In addition, another study found that with trisyllabic nonwords in particular, the majority were given initial stress (Ernestus & Neijt, 2008). This could be related to a suggestion by Levelt, Roelofs & Meyers. (1999) Trochaic is the default stress pattern and stimuli that are considered “irregular” do not possess any useful statistical information to infer stress patterns and thus people default to a regular stress pattern when processing these words.

It is also hypothesised that if stress was done in serial participants will produce significantly more errors when responding to irregularly stressed words. In particular, irregular trochaic words (e.g. car**bon**ic), which should have second syllable stress, but are instead given first syllable stress. This would be due to the nature of serial processing, there would need to be some form of correction due to inconsistencies and thus should occur late. Finally, in terms of reaction times, we should also expect words that begin with iambic pattern to be much slower than those starting with trochaic pattern.

Should all these predictions not occur, the results will support a parallel model that predicts participants are largely unaffected by the high working memory load, apart from an overall slowing down (i.e., different types of word will not be affected differently). There would be no differences between regularity or morphology in relation to reaction times. That is, there should be also be no substantial difference in reaction times between high and load conditions. Participants should also have more correct stress placement or more varied stress positions. It is interesting in particular to see how well participants do on words that are stressed irregularly (e.g. car**bon**ic), if they do well, it does imply that they are able to successfully process the final syllable cue to infer stress patterns. We also expect to see an effect on reaction times. They should be slower than regularly stressed words and the differences are exacerbated in the high load condition.

Method

Participants

Twelve native speakers of Australian English aged between 18 and 55 participated in the experiment (six males and six females). They were people known to the experimenters and recruited via word of mouth. Participants were given information about the study and were asked to read and sign a consent form. The study was approved by the University of Adelaide Ethics Committee.

Stimuli

The stimuli used in this study consisted of 208 words and 208 nonwords. The words were taken from Perry (2017) and could be divided into 4 groups of 48 items based on whether they had first or second syllable stress (c.f., CARbonate vs. abDUCted), and whether they were stress regular or irregular (c.f., CARbonate vs. carBONic), defined based on whether the first two-syllable had the same stress as the word from the majority of the time. The nonwords were created by taking the words and changing their onset (e.g., migrating vs. pigrating) where possible. For a small number, additional letters needed to be changed. The vast majority of the words contained 3 syllables although there were a small number that used a bound morpheme with two syllables which meant that the words and nonwords had 4 syllables each. The stimuli were balanced on word frequency, letter length, orthographic neighbourhood, number of morphemes and concreteness. All measures were taken from the English Lexicon Project, except for frequency and concreteness. Further lexical statistics can be found in Perry (2017). An additional sixteen practice words were used at the beginning of each memory condition.

The words were split into two counterbalanced groups based on whether they were to be presented in a high or low memory load condition. This was done by dividing each of the 4 groups into two, meaning there were 8 groups of 24 items. This was done in a way such that the initial morpheme of each word appeared in only one list (e.g., carbonless and carbonic appeared in different lists). A further two counterbalanced groups were used based on whether the word was presented in the high or low memory condition first. Participants were randomly assigned to one of four counterbalanced groups depending on when they completed the task.

The presentation of the stimuli was done with the program PsychoPy (Pierce et al, 2019). At the halfway point, participants are then asked to repeat the task in the other condition.

Task description

Participants were seated in front of a computer screen. They were given information about the experiment and were asked to fill out a consent form. Before beginning the exercise, they were given examples on what it is meant by first or second syllable stress. They are advised that when selecting stress, they do so quickly and were encouraged not to think about the word, but rather, indicate what first comes to mind. For non-words, participants were asked to select which they think is most correct. Finally, they were informed that they can stop the experiment at any time.

The high memory load condition was structured such that each block of trials contained 8 words. Before each block, a set of 3 numbers (1-9) appeared that participants had to remember, and this lasted for 3 seconds. Following this, a blank screen appeared for 500ms, and the first word of the block appeared. Participants had to judge whether stress appeared on the first or second syllable of it by pressing the left or right arrow key, after which the word disappeared. A blank screen then followed for 1 second, and the next word appeared. This was repeated until all 8 words in each set had been presented. After that, a screen appeared where participants were prompted to type in the numbers that occurred at the start of the set. The low memory condition simply presented each word one after the other with a blank screen occurring for 1 second between them, and participants judged whether each word had first or second syllable stress until all of them were done. Within both high and low memory blocks, the words were presented in a pseudorandom order.

Results

Participants responses (first or second syllable stress) and reaction times were recorded. The statistical analysis was completed with the R statistical package using the lmer and emm packages. The 32 Filler words were removed from both the items and reaction times data. Data analysis with the reaction times was doing using all responses excluding outliers. A mixed model using a 2 Morphology (Trochaic/Iambic) x 2 Stress Regularity (Regular/Non-Regular) x 2 Memory load (High/Low) ANOVA was used to examine both response probabilities and Reaction Times (RT's), with the response probabilities being examined using a binomial distribution. The three factors were entered as both fixed and random factors. With the random factors, a random constant and random slope was calculated for each participant and item used (see Baayen, Piepenbrock & van Rijn, 1993). Note that because of this, we estimated the degrees of freedom for the RTs using Satterthwaite's method, and for the response probabilities we used a Chi-square distribution. Similarly, we estimated partial eta-squared as is often reported. The mean results of the Reaction times and response probabilities appear in Figures 1 and 2.

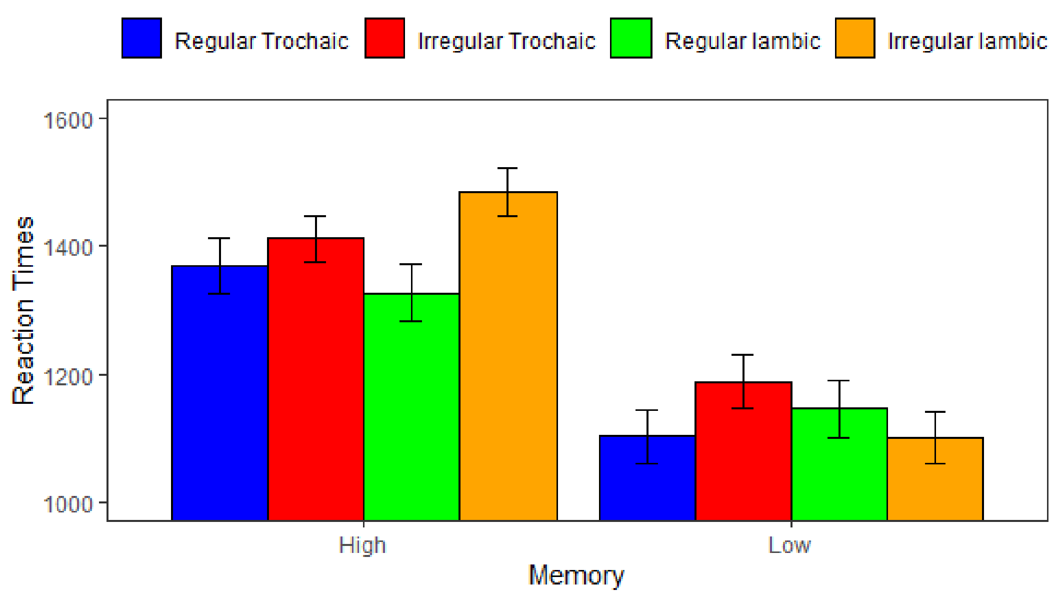

Figure 1: Mean reaction times as a function of stress regularity and the stress of the initial morpheme, in high and low memory load conditions. Error bars are +/- 1 SE.

Initial screening of the RT data was done to remove items responses +/- 3SDs. This removed 1.4% of the data. As seen in Figure 1, there was, unsurprisingly, slower reaction times in the high load condition. Most strikingly for this field, is that participants were, generally, extremely slow, with means responses over 1 second in all conditions (simple reading aloud tasks usually have means of around 500ms; Balota et al., 2007).

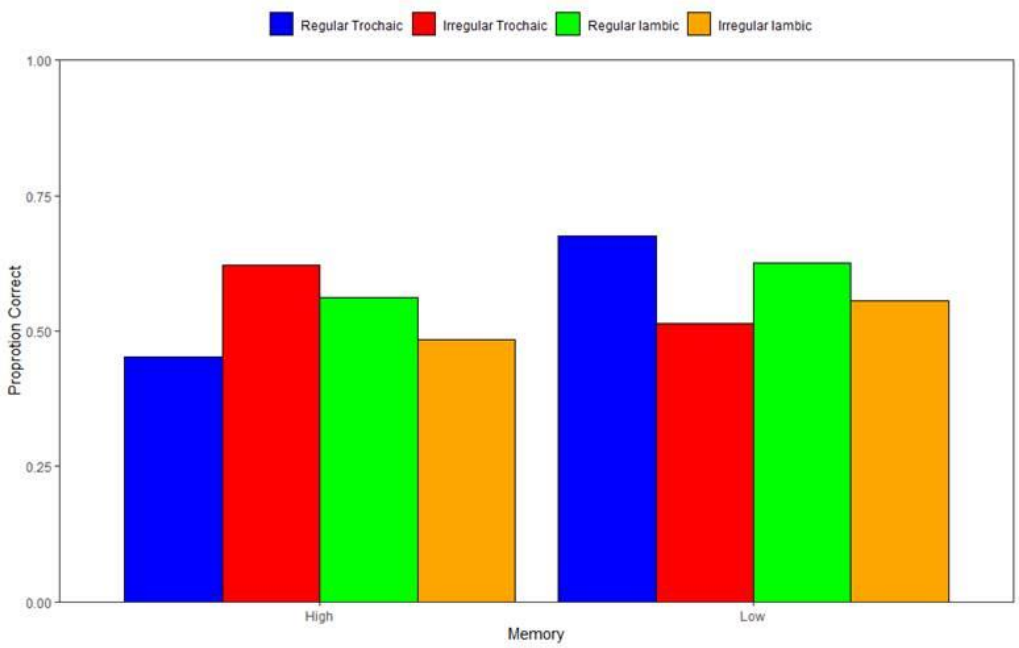

Figure 2: Mean Response probabilities as a function of stress regularity and the stress of the initial morpheme, in the high and low memory load conditions.

The response probabilities suggested that participants were very poor at doing stress judgements, with an overall accuracy rate of only 56%. Whilst it is well understood that untrained reporters often have trouble judging secondary stress, clearly this task shows they have trouble making explicit judgements even with primary stress.

Reaction Times

The results from the ANOVA run on the RTs showed a significant effect of Stress Regularity (F(1, 29.72) = 4.93, p=0.03, partial eta2=0.14). Mean reaction times showed that irregular words took slightly longer time to be processed (1296ms) than regular words (1236ms).

A 3-way interaction between morphology, memory and stress regularity was also significant (f(1, 265.03) = 5.30, p=0.02, eta2=0.02). This was caused by a different pattern of results occurring in the high and low load conditions. We therefore performed a number of post hoc comparisons on the data[2].

In terms of the high load condition, there appeared to be an effect of irregularity that was larger with iambic words than trochaic words. Post-hoc testing this showed that there was a significant difference with the iambic words (t(99.6) = -2.80, p=0.006)[3] where the irregular words were slower than the regular ones (1486ms vs. 1327ms). Alternatively, individual comparisons showed the regularity effect was not significant (t(182.6) = 0.82, p=0.41) with the trochaic words (1396ms vs. 1413ms).

In the low conditions, the irregular trochaic words appeared slower (1100ms) than the regular ones (1102ms), and the reverse pattern was found with the iambic words. Iambic irregular words (1100ms) were faster than regular words (1146ms). Post-hoc testing showed that neither the differences were significant (p>0.05).

These comparisons show that memory load does have an impact, with Reaction times in the low load condition faster than the high load condition, and iambic words in particular being more affected in the high load condition. Finally, it is more difficult and to infer stress for words

[2] Note that we used lsmeans package, which report results in z scores
[3] T-value will be used instead of F-value

that irregular, and this is especially noticeable for words that are irregular and iambic. This implies that words such as **ab**ductee, which are already hard to process as it deviates from a regular iambic pattern, becomes even harder in higher load conditions.

Response Probabilities

The results of the ANOVA showed that there was a main effect of morphology ($z=4.98$, $p=<0.001$). The results showed that trochaic words had a higher accuracy (59.25%) than iambic words (52.75%).

There was also an interaction between Morphology and Memory ($z=2.60$, $p<0.009$). Under a high load condition, Trochaic words were more accurate (59%) than Iambic words (53.5%). The pattern is similar for a low condition, where Trochaic words were also more accurate (58.5%) than iambic words (52%).

There was also a significant main effect of stress regularity ($z=-3.62$, $p<0.0002$). The results showed that the regular words were responded to significantly more accurately than the irregular ones (56.75% average vs 54%), although the actual difference was small.

There was also a 2-way interaction between Morphology and Stress regularity ($z=5.19$, $p<0.001$). This was caused by the stress regular trochaic words being more accurate (64.5%) than their iambic counterparts (60.5%). While stress irregular trochaic words (48.5%) were *less* accurate than the stress irregular iambic words (55%). Post-hoc tests showed there was no interaction with trochaic words and regularity, but there was a significant interaction was between iambic words and regularity. This was in the form of iambic and stress regular words ($z=2.23$, $p=0.02$) and iambic and stress irregular words ($z=2.81$, $p<0.05$). The results show that regular words (53.5%) were slightly more accurate than irregular (52%).

Like the reaction time data, there was a 3-way interaction between morphology, stress regularity and memory ($z=3.91$, $p<0.05$). This was also caused by differences between the high and low condition.

Post hoc testing indicates that there is indeed a significant interaction between high memory load and stress regularity ($z=3.70$, $p=<0.05$). Furthermore, the effect of irregularity is stronger with iambic words ($z=3.97$, $p=<0.05$) than trochaic words. Under high load, iambic regular words were 45% accurate, but, irregular iambic words are overall *more* accurate (62%) than when under low condition (48%). This is in contrast to the results thus far, as iambic words, especially under high load condition, have slower reaction times and more incorrect responses. Additionally, the regularity effect was not significant with trochaic words ($z=1.58$, $p=0.11$) (64.5% regular vs 52.5% irregular).

In the low condition, no instance of irregular words being more accurate exists. Iambic regular words were more accurate compared to irregular iambic words (56% vs 48%). A similar pattern can be seen with trochaic words (62% vs 55%). Thus, there appears to be no effect of stress regularity on response probabilities in low memory load ($z=1.80$, $p=0.07$).

Overall, it seems that Trochaic and words that are regularly stressed are the most accurate. Like reaction times, irregular words seem to suffer more, although the differences in accuracy was small compared to the larger difference in reaction times. Once again, it appears iambic words are harder to process than trochaic words, possessing a lower correct response probability rate. Irregular words also seemed difficult to process, however, this was only for irregular trochaic words, irregular iambic words were far more accurate under a high load condition.

Non-words

Concerning non-words, the mean reaction time in the high load condition was 1470ms and 1174ms in the low condition. Despite the large difference, the results were not significant (Fs = p=0.26). which is likely to be due to the small number of participants tested.

A similar pattern can be observed with non-words in terms of memory load. The rate of first syllable stress was 57% in the high load and 56% in the low load condition, indicating that for non-words, accuracy is no better than chance.

Both of these results indicate that the stress judgments of participants were largely unaffected by memory load.

Discussion

The aim of this thesis was to explore the predictions of stress being processed in either a serial or parallel way. Another aim was to examine the role of working memory in this process.

It was predicted that if stress was processed serially, there would be a gravitation towards first syllable stress, regardless of word or nonword status, although this would be more noticeable in the high memory load condition. We would also expect this to occur with irregularly stressed words, with reaction times dramatically slower in high load conditions for words that started with a trochaic morpheme.

The alternative predictions were that if processing occurs in parallel, participants would only be slightly affected by working memory load. Reaction times between memory loads should not differ, and this would be the case for both morphology and regularity. In addition, error rates should not interact with stress irregularity or morphology. For example, irregularly stressed words should not be far less accurate. Thus, there would be far more varied response patterns.

Trochaic Default

Under a high working memory load, it was predicted that participants would move away from a system that uses cues, and simply apply a trochaic default pattern. The response data under high load somewhat met this prediction. Regular trochaic words were generally more accurate than their iambic counterparts. However, the result that really does lend support to this default is that irregular iambic words (i.e., words with an iambic root morpheme) were most accurate under a high load. This is surprising as irregular words have a generally higher error rate compared to regular. This gravitation to a trochaic default can be explained in a word such as **ab**ductee. This word is stemmed from ab**duc**tion, which requires second syllable stress and is correct for an iambic word. Because of the irregularities between the irregular first syllable stressed **ab**ductee and regular second syllable stressed ab**duc**tion; this should cause **ab**ductee to be susceptible to more incorrect responses. However, participants seem to be more accurate at correctly giving the irregular **ab**ductee trochaic stress than the regular ab**duc**tion. This can be interpreted as participants unintentionally giving correct stress, especially when under a high memory load demand – that is, if they could make a simple decision where stress may go, they may simply have used a trochaic default.

This result shows support for a possible Trochaic default when assigning stress. This result is similar to the study done by Domahs et al (2014). This also lends support for the linguistics perspective, where it is assumed that the majority of words are 'unmarked', in that they do not have stress specified, and simply get given the default stress (which in English is trochaic) when other information is not present**.** Furthermore, it is in line with trochaic stress being dominant and regular and that anything that is not first syllable stress is deviant and irregular (Levelt et al, 1999).

Perhaps a reason as to why participants defaulted to first syllable stress is that the high load hindered the participants ability to efficiently access correct phonological representations of the word. That is, they fail to accurately encode sequences of phonemes within the word. It could be that the participants were unable to see associations between syllables or cues that participants just chose the first syllable, because of computational ease. This possibility has been seen in other studies such as one by Colombo, Fonti & Cappa. (2004). The study shows this possibility with people who suffer from Alzheimer's. It indicates that the more severe the disease, their ability to access phonological representations to see associations is compromised, and there was a gravitation to first syllable stress regardless of word type. Perhaps a similar idea can be inferred with those who are under a higher memory load.

Reaction Times

We also expected that words with trochaic root morphemes should be especially slow when they are irregular (e.g. car**bon**ic) as they need to be corrected by the final morpheme, and thus will occur late if processing occurs in a serial fashion. Thus, we expect reaction times to be far slower. Based on the reaction time data for the high load condition, this somewhat appeared to be the case. Irregular trochaic words appear to be slow, although this result failed to reach significance. We also expected this for words with iambic root morphemes (e.g. ab**duct**ee), but this was not found, possibly due to a bias towards trochaic stress. This was seen in irregular iambic words, which were the slowest, indicating that participants took a long time to resolve the stress pattern. In addition, it also appeared that regular iambic words were the quickest. We believe stress regularity may be a factor for these results.

Stress Regularity

The results show that there is a main effect of stress regularity for both Reaction times and Response Probabilities, in both instances regular words were generally either faster or more accurate than their irregular counterparts (for accuracy, this is a marginally small difference).

Even though working memory load may have caused irregular iambic words to be more accurate, it seems that with irregular words in general, both trochaic or iambic, it is extremely hard to correctly infer stress. This is especially noticeable with the reaction time data, as under high load, irregular words were the slowest to be attended to. The interaction between morphology and stress regularity (response probabilities) indicated that this was significant for iambic words, that is, irregular variants were slightly more inaccurate than regular words. This does support previous research that words with stress patterns that are not typical are poorer in terms of accuracy.

One possible reason for this is participants are hampered by inconsistent stress patterns and **cues,** especially if processing is done in a serial fashion. If one were to break down a word into each individual syllable when comparing regular and irregular words, the inconsistencies are noticeable. In an irregular trochaic word such as carbonless the first two syllables, **car** and **car**bon, are both stressed on the first syllable. Once the processing of **car**bonless occurs, the first syllable stress is still present and has not changed, thus processing is stress pattern is easily complete and quick. However, an irregular word such as car**bon**ic has second syllable stress. The first syllable, **car**, is trochaic by default, which is incorrect, followed by **car**bon, which also has trochaic stress, which is also incorrect. Once car**bon**ic is processed, the participant has almost been "primed" with the incorrect stress pattern, thus inferring the correct second syllable stress pattern would be much more demanding.

A similar idea could be used to explain why a regular iambic word such as ab**duc**tion was the least accurate among high condition. Despite it being a regular word, it still suffers from the same computational issues that irregular trochaic words had due to the nature of serial processing.

Our reaction time data is consistent with studies such as those by Arciuli & Cupples (2006), that reaction times are quicker for regular words, but are inconsistent with results such as (Burani & Adiurno, 2004), which state that irregular words are attended to faster. Perhaps misleading cues are setting up for overall slow processing. Each time the correct stress pattern is chosen, processing is quick and unaffected. But when a syllable in unexpected position arrives, processing is slowed down. So, we would expect irregular variants of both trochaic and iambic words, such as car**bon**less and **ab**ductee respectively, would be much slower than their regular counterparts, for example, **car**bonless and ab**duc**tion respectively. Although as seen in our data, misleading cues can also lead to an unintentionally correct outcome.

Cues

In our study, both the initial and final morpheme predicted stress, and it appears that both are not reliable. It would appear that a reason for trochaic default is that cues are simply biased towards the initial syllable, and as explained before, can hinder the computation of stress.

But ending cues are also just as important. Word endings are seen as an influential cue in determining correct responses. Arciulli & Monaghan (2010) found that compared to word beginnings, which were less informative endings were more indicative of stress position. This is problematic if there was a first syllable default as some participants can select stress before correctly understanding the final syllable. This is especially so as final syllable cues, even though they are variable in their predictability, they are generally used to indicate the stress position of irregularly stressed words.

The effectiveness of word ending cues could also hampered if said cue is of low frequency. One way of understanding this is the idea of “stress neighbourhoods”. That is if the ending syllable of the word is shared with other words (Large neighbourhood), the accuracy of overall stress placement would be much higher than those words that do not share its ending with other words (Small neighbourhood or Low frequency). Furthermore, Pagliuca & Monaghan (2010) reiterate this by stating word ending cues are only used if that same word ending is shared with other cues. However, this seems unlikely given that this explanation is guided by parallel processing principles that default stress pattern does not exist. Something that none of our results seem to support. It implies that participants are able to process the final cue, to see whether it does share it with other words. Considering that there is evidence for a trochaic default, this possibility seems unlikely.

Finally, there is a possibility that readers may just read the first two syllables, without actually looking at the final cue, this could have led to the higher error rates with irregular words, simply because they do not process the final cue. In addition, this could also provide an explanation for a possible trochaic default. This would be due to task demands as the aim was to select either first or second syllable stress. Perhaps they would be more compelled to do so under high load, to offset the demands of working memory.

Perhaps another possibility from reading only the first two syllables is that the bias towards the initial stress becomes even stronger, especially if processed syllable-by-syllable. To illustrate this, take the word abduction. The first two syllables comprise of the initial morpheme abduct. The first syllable, "Ab", being a single syllable, is stressed quickly with the regular trochaic stress, once the word abduct is presented, the move to stress the second syllable ab**duct** would be slower. Perhaps the participants would still only have the first syllable "ab" processed and has yet to make a judgement about abduct. Therefore, they would input first syllable stress instead of the correct second syllable. This could provide an explanation for why the regular iambic word ab**duc**tion was the least accurate (and why they were fastest). If participants still lingered on the first syllable, this could provide another explanation as to why irregular iambic words (like abductee) were unusually accurate.

However, for this possibility to be effective, there is an expectation that the participants are able to strategically block out the final syllable and just focus on the initial morpheme. Under high load condition, this seems unlikely as participants would have to make an attempt to do such thing as they are also doing an additional memory task. Furthermore, the literature indicates that reading words with spaces is difficult. In this case the initial morpheme and final syllable would be split (e.g. abduct_ion). Thus, it would not seem strange to think that ignoring words within a word would be difficult. Similarly, some studies indicate that that all orthographic forms are processed automatically, thus it suggested would be easier to just make a decision by processing the entire word as opposed to processing and ignoring certain syllables (Perry, 2017). Although our data suggests that words are indeed not processed at once. Even though there are problems with how people could block out certain syllables, it could be a possibility with this data, due to a possible trochaic default, in addition to cues biasing first syllable stress anyways.

Morphology

We found a main effect of morphology as well as an interaction between morphology and memory. This was present in just the Response Probabilities data. Trochaic words appeared to be more accurate than Iambic words. This was seen in both conditions but more obvious in the high load. The simplest explanation for this is that trochaic words (and trochaic stress assignment) in English are simply more common than iambic stress. This can also be seen with an interaction concerning stress regularity and morphology, although this was significant for iambic morphology and response probabilities. Our high load response results seem to be consistent with studies such as those by Colombo (1992) and Colombo & Sulpizio (2015). That is, the use of dominant (default) stress can cause words to be named more accurately than those that do not seem to bear such pattern.

Frequency and Regularity

Another reason for the effect of stress regularity in both reaction time and response data is the Frequency x Regularity effect. Low frequency words that are irregular or inconsistent are usually read slower and produce more errors than low frequency regular words. This is due to low frequency words in general being uncommon as well as producing more irregular patterns. In comparison, High frequency words are words while not necessarily possessing dominant stress they may since be able to be recalled directly from memory as a whole, thus, irregularity, unlike low frequency words, may not matter.

Many studies have demonstrated that High frequency regular words can be processed quickly due to one already possessing the ability to perform a memory look up. Low frequency words, especially those that have irregular processing. Some models that attempt to process these less frequent words often just default to assigning the most dominant stress pattern (Colombo et al, 2004), as our results may have showed. One reason why some of the results here may lack significance, is that, apart from the small sample size, the word set includes both high and low frequency words, and the high frequency words may not show stress irregularity effects. If more stimuli could be chosen, perhaps it is worthwhile to look more at effect of stress regularity in low frequency words, to see if an effect of irregularity is larger.

Non-words

Our nonword data seems to demonstrates that our participants assignment of stress seems mostly unaffected by any of the factors we investigated -- regularity, morphology or memory load. This is surprising, as there was an expectation that effects on error rates would be at least present. In the literature, non-words seem to rely more on the abilities such as phonological encoding more than normal words (Coalson & Byrd, 2017). In one Italian study, for example, nonwords, especially with ambiguous endings see a jump in their error rates and the advantage of using first syllable dominant stress decreases (Colombo & Sulpizio, 2015)

This null effect was different to our predictions, where we expected that non-words would default to initial trochaic stress in the high memory condition. This was not the case – the rate of trochaic stress was almost identical in the high and low memory conditions. This was also in contrast to Domahs et al (2014), suggesting non-words were most likely to affect first syllable stress than second. However, their study used a correlational design and ours used an experimental manipulation, and thus these differences may be attributable to task design differences. Alternatively, they may be due to their study using German and ours being English given English stress is more variable than German stress.

The reaction time data also did not support our predictions if processing was slowed down (due to load) then the sub lexical processing (i.e. not simply retrieved from memory) should cause participants to linger on the first syllable compared to if the word was processed quickly (in parallel), in which case such lingering would not exist. This would occur if words are processed syllable-by-syllable. In our data, while the differences in non-word reaction data did exist, the difference was not significant. This may be due to the small sample size as the results went in the expected direction but were not significant. Response probabilities also did not support this predication, as seen above, the rate of first syllable stress between both conditions, did not differ.

Low Condition

In the low condition, the response probabilities and reaction time data appear to move in a direction that seem to support parallel processing. For instance, there does not appear to be an obvious interaction between responses and regularity or morphology. However, these differences did not reach significance.

Further issues

An unexpected result that has some implications for the rest of the results was that participants either did not understand or struggled with the task immensely. The error rates were very high for most participants, with some doing no better than chance. The reaction times were also quite slow for a task of this nature, averaging around 1500ms, unlike normal reading aloud tasks which take about 500ms (Balota et al., 2007). This has not been found in studies examining stress judgements in disyllables (e.g., Arciuli & Cupples, 2006). There are a few reasons why accuracy was poor and reaction times slow.

Implicit Reading

Most of reading is done implicitly. This means that without much thought, people are able read without thinking how to correctly pronounce words. In this study, participants were explicitly asked to think about where stress is placed. They had to silently read and then select the words' correct stress position. For many this would seem unnatural and it is not strange to think that participants would have never had to think about where stress lands under ordinary circumstances. They also had to monitor their own representations about words, and there are many things that are interfering with their judgements, such as an additional task in the high condition). Notably, we asked them to make a judgment on the first two syllables, and this already may have been difficult as they would have needed to abstract their judgements away from the actual word to a morpheme which may have differed in stress.

At an individual level, there is a possibility that participants may have incorrectly perceived stress. This is because what stress is in English is not obvious, and so the fact trained observers can make judgments is because they understand what they are making judgements about. As noted in the grammar of Hammond (1999), stress is "syllables that are more prominent than their neighbours… stressed syllables would be longer, louder, or higher in pitch than unstressed syllables. While this seems generally true, it is not an absolute, and the phonetic correlates of stress are quite complex', and thus making judgements may well be difficult for uniformed observers.

Alternative Strategies

Perhaps an explanation specifically for the slow reaction times is that people may be implementing different strategies in an attempt to accurately infer stress. This could be the case when cues they are familiar with fail to elicit the correct response. This could also be true for a word they are not familiar with. Participants would most likely use their knowledge of spelling-sound relationships (e.g. meta-linguistic knowledge). This knowledge encompasses multiple processes and cues, which participants try to introspectively draw upon with their working memory. Whilst the intention of this is to maximise accuracy, it is rather complicated and open to bias, quite unlike normal reading.

Limitations

This study has a number of limitations, firstly a stress judgement task was used. This may have exacerbated the problems associated with what stress actually is, since participants are not actually reading the words aloud. A reading task would have been better as it would allow participants to naturally say the word, without thinking about where stress should go or what stress is. In addition, a stress reading task would also circumvent the issues surrounding poor reaction times as, once again, it would allow them to simply to say it. In addition, the sample size was very small, and so many of the effects need to be interpret with caution.

Finally, there may also be a possibility that the participants may have just misinterpreted the task altogether, especially if starting with the high load task. They may have seen the main task as remembering and imputing numbers correctly, as opposed to imputing stress.

Conclusion

This study used a working memory load manipulation to help examine whether stress is processed in serial or parallel when reading. Significant differences in reaction times and stress position judgements were found in the high load condition and there also appears to be a substantial effect of stress regularity. These results are suggestive of serial processing. However, there was no evidence of serial processing with non-words. In sum, there is at least some evidence words are processed in serial and that irregularities between spelling and sound can affect these processes. However, there were a number of null effects found that were unexpected, particularly with the non-words, which made the results difficult to interpret and the study itself featured many limitations.

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