The Connectionist Dual Processing Model of Reading and Visuo-Spatial Attention: The Dissociation of Two Visual Processing Factors on the Model's Underlying Mechanisms.

Anna Holt

This thesis is submitted in partial fulfilment of the Honours degree of Bachelor of Psychological Science (Honours)

School of Psychology

University of Adelaide

September 2021

Word count: 9146

Contents

List of Figures

List of Tables

Abstract

In recent years there has been a shift towards more sophisticated computational models in typical reading. One such model is the Connectionist Dual Process (CDP++) model of reading aloud. There are arguments about the extent to which and how visuo-spatial attention is used when reading. Whilst many factors have been shown to correlate with reading performance, this thesis restricts its focus to two visual processing factors: Visual Attention Span (VAS) and focused visuo-spatial attention. Overall, we are interested in whether two types of attention can be dissociated on the lexical and sublexical pathways of the CDP++ model. This was tested through three tasks: a simple 250 word reading task, a VAS task, and a Posner task. Quantitative statistical methods were used to determine the relationships between the tasks. Whilst not all of our predictions were confirmed we did find a number of useful insights into reading. A wide attentional window allows pronunciations to be generated correctly by the lexical route. It was found that the Posner task may suffer from validity problems in terms of it measuring the desired attentional process. In the future, tasks likely to measure attention in reading with higher validity may help us better understand the dissociation that has been reported in the literature. Elucidating this is important because the way factors affect how reading works may be used to help understand dyslexia, as well as predict outcomes from training programs.

Keywords: reading, visuo-spatial attention, connectionist dual process model

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.

Anna Holt

September 2021

Contribution Statement

In writing this thesis, my supervisor and I collaborated to generate research questions of interest and design the appropriate methodology. I conducted the literature search and completed the ethics application with the help of my supervisor. My supervisor provided the experimentation room with the equipment to run the provided MATLAB scripts. I was responsible for all participant recruitment and testing. My supervisor provided the initial code for analyses in R Studio for the statical analysis and graphing, which I changed and edited to analyse the results. I wrote up all aspects of the thesis; my supervisor reviewed sections throughout the writing process.

Acknowledgements

This thesis is a culmination of an immeasurable amount of hard work, and it would not have been possible without key people supporting me along the way.

Firstly, I want to thank my thesis supervisor Dr. Conrad Perry, whose guidance, support and explanations were crucial in helping me develop my understanding and a keen interest in this topic. Furthermore, his patience in explaining the nuances of computer code to me has taught me so much.

Secondly, I would like to thank my partner, who helped me massively by listening to me talk nonstop about my thesis' theory and results and what I thought they meant in the context of my thesis. I am grateful for your kind words and support throughout this busy year.

Finally, I'd like to thank my parents and my partner's parents for taking the time to support me throughout this process and always being happy to listen to me ramble on about statistical minutia.

The Connectionist Dual Processing Model of Reading and Visuo-Spatial Attention: The Dissociation of Two Visual Processing Factors on the Model's Underlying Mechanisms.

There are arguments about the extent to which and how visuo-spatial attention is used when reading. A number of people have looked at simple correlations between aspects of this type of attention and reading performance with some finding a relationship (Facoetti et al., 2020), but they have not directly tested the possible effect on underlying reading mechanisms. Elucidating this is important because the way such factors affect how reading works can be used to help understand typical reading development and reading disorders, as well as to predict likely outcomes from different types of training programs. One such reading disorder is developmental dyslexia, a neurocognitive disorder which is characterised as a specific learning disability (Lyon et al., 2003). Dyslexia is signposted by difficulties in accurately recognising words, slow reading speed, poor spelling and other difficulties related to literacy. It occurs in approximately 5-12% of children, and many people have such difficulties for life (Peterson & Pennington, 2012). Thus, understanding the factors that underly it, including how they are used in typical readers, is important.

Why Is Reading Hard?

Gough and Hillinger (1980) have described reading as an "unnatural act". A likely reason that reading is hard for many is that, unlike speaking and listening, which can be obtained without any formal education, and indeed has often been argued to be innate, reading is clearly a skill that must be learned. Thus, it is unsurprising that spoken language is learnt very differently to written language (Treiman, 2018). In this respect, children need to be explicitly taught how their language maps onto the corresponding writing system, and it takes years before they can master a language like English (Castles et al., 2018).

One of the most important things children need to learn is the relationship between their writing system and its speech sounds. This is obvious to most adults, but for preliterate children, illiterate adults or adults that use non-alphabetic writing systems, this is not an obvious connection, demonstrating the unnatural aspect of reading (Morais et al., 1979). Deciphering the code where marks on a page represent units in their required language is a challenging task and represents an important process in reading – if one cannot do it, then learning to read is very difficult, as rather than associate letters with sounds, one would be forced to remember words purely visually. Whilst there are cases where people can do this (Levy & Lysynchuk, 1997) they are very rare, suggesting that such a strategy is not viable for most people.

There are at least two aspects of reading that are important when learning the connection between spelling and sound. One is being able to remember the letters in words so one can read words with non-obvious spellings, of which there are many in English (e.g., *aisle, word, bear, hear, who*). The other, which is less obvious, is being able to break letters down into groups and spell out words. Developmentally, this allows children to read words they have not seen before, and it is well known to still be very important in adult reading (Hulme et al., 2015). In this respect, there are large numbers of studies showing the importance of phonology (Hulme, Nash, Gooch, Lervåg, & Snowling, 2015; Solity and Vousden, 2009; Snowling, 2001; Lloyd & Wenham, 2000; Share 1995) as well as visual processing, the focus of this thesis.

Models of Reading

Early models of typical reading were purely verbal and qualitative measures that were used to describe the reading process (Perry et al., 2007). These verbal theories were made more formal and more explicit first by Morton (1969) in the form of a box-and-arrow model, which showed how different types of information could interact in word recognition. In this case, the boxes represented representations (e.g., ‘letters’, ‘mental lexicon’) and the arrows represented the flow of information between them (e.g., the flow between letters and the mental lexicon).

In more recent times a number of much more sophisticated models have been proposed. The once purely verbal theories were replaced with computational models, which allowed word recognition and reading aloud to be examined in a more sophisticated manner (Perry et al., 2007). Another type of model proposed is based on a largely behaviourist paradigm known as connectionism. This type of modelling aims to describe the basic process of reading through the use of interconnected networks of very simple units or nodes. It thus moves away from the more general box-and-arrow type model proposed by Morton, although still has representational levels (e.g., graphemes, such as ’ch’, and phonemes).

The most well-known model in this domain is the Triangle model (Seidenberg & McClelland, 1989; Plaut et al., 1996). Two other types of models have also been proposed. One of these is more similar in style to what Morton proposed, but vastly more sophisticated. It is known as the Dual Route Cascaded (DRC) model of reading (Coltheart et al., 2001). In this thesis, this model will not be examined further, as it is largely superseded by a hybrid model which contains both representations similar to that of Morton, but also integrates statistical learning mechanisms more similar to that of the Triangle model. This is known as the Connectionist Dual Process (CDP++) model of reading aloud.

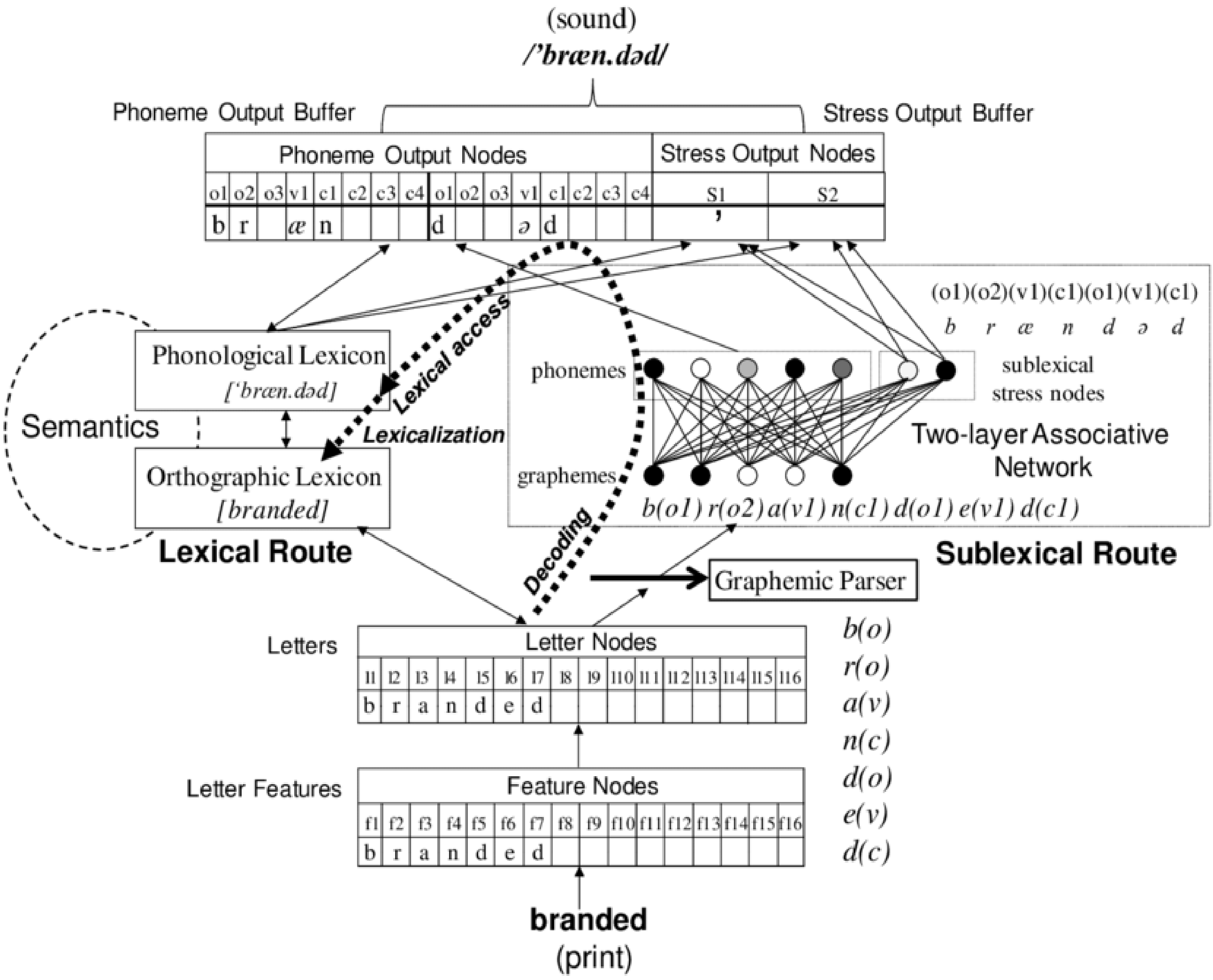
Connectionist Dual Process Model

Perry et al. (2007) sought to improve the limitations of the DRC. Figure 1 shows the latest version of this, the CDP++ model (Perry et al., 2007; Perry et al., 2010; Perry et al., 2013). The CDP++ Model of reading aloud encompasses two halves. One side demonstrates the way we are able to remember words (lexical route), the other half is one in which we are able to impute pronunciations without knowing the word itself (sub-lexical). These two different procedures for converting print to speech work in parallel until one pathway wins out and produces the word to speak (Rastle & Coltheart, 1999).

The lexical route starts at individual letters, based on McClelland and Rumelhart's

Figure 1

The Latest Version of the Connectionist Dual-Process Model of Reading Aloud (CDP++ parser) (Perry et al., 2013).



(1981) interactive activation model. These letters then activate orthographic entries in the orthographic lexicon. This is implemented by each letter overlapping with currently held letters of words in the orthographic lexicon, and words that do not share those letters are inhibited. Letters are mapped onto words using a position-specific one-to-one correspondence, meaning that the first letter in a word is activated or inhibited by the first letter, the second letter in a word is activated or inhibited by the second letter, and so on. Subsequently, once entered in the orthographic lexicon this then activates entries in the phonological lexicon. This encompasses the same process occurring, with activated entries in the phonological lexicon activating or inhibiting phoneme units in the phonological output buffer. This allows the generating of a pronunciation of the word that can then be read aloud (Perry et al., 2007).

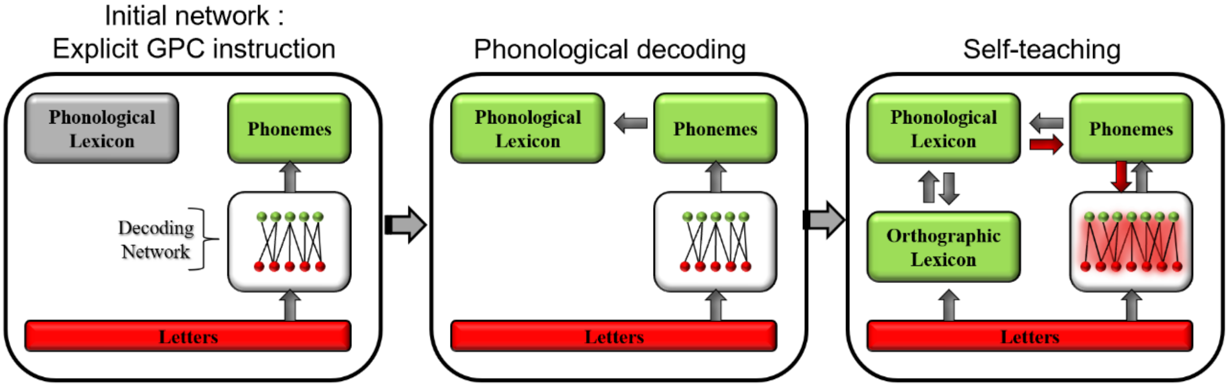
The sublexical part of the model consists of a two-layer network and shows how the graphemes in letter strings are converted into phonemes. The model assumes that, when the sublexical route processes letter strings, only the portion of the string that is contained within an “attentional window” is available. The size of the attentional window is fixed, however the model makes the assumption that the maximum attentional window size differs across languages and reading development (e.g., Perry, Ziegler, Braun, & Zorzi 2010). Additionally, the window could be forced to operate at a lower size in differing reading contexts. The model learns to select and categorize the grapheme furthest to the left at any given instance as the attentional window moves across the letter string. A second assumption the model makes is that it has a memory for graphemes that have been previously selected and categorized, and thus a grapheme chosen at any given moment in time is context sensitive based on those that have come before it.

An example of the way CDP++ processes the word *branded* occurs in Figure 1. The word is broken down to its visual features and letters from the printed word. From there, the word can be read in two different ways. On the left-hand side of the picture, how the lexical look-up method is implemented is shown. To activate this route all letters in the string that make up the word *branded* must be activated. This being that they overlap with that specific word in the mental lexicon and contact the orthographic lexicon in parallel (i.e., the mental dictionary of written words). After that semantics and the phonological lexicon (i.e., the mental dictionary of spoken words) can be contacted. Finally, the phoneme output buffer can be contacted. This is where the final phonemes are put before speech output. The part of the model displayed in the right half of the picture is the sublexical route. As can be seen, the graphemic parser first breaks the letter string down into graphemes. From there, graphemes are put in the sublexical network. When this occurs, that networks start imputing the likely phonemes in the word, and these are put in the phoneme output buffer, and can compete with those put there from the lexical route for speech output. Word stress works in essentially the same way.

Figure 2 encompasses Perry et al. (2019) schematic illustrating the initial teachings of grapheme-phoneme correspondences (GPCs). This entails supervised teaching of these GPCs, such as b → /b/, and thus uses a simple associative learning rule between the cue, b and the outcome /b/. In a natural environment, this learning becomes unsupervised, and this is an example of implicit statistical learning procedures- where one tacitly can pick up

Figure 2

Perry et al.'s (2019) Schematic Illustrating how After Initial Teaching on a Small Set of Grapheme-Phoneme Correspondences the Decoding Network is Able to Decode Words That Have a Pre-Existing Representation in the Phonological Lexicon but no Orthographic Representation.



regularities. In Figure 1 this process of self-teaching is illustrated through the thick dotted lines (i.e., letters→ sublexical decoding→ output nodes→ phonological lexicon→ orthographic lexicon).

Whilst there are many factors that have been shown to be correlated with reading performance, here we will restrict our focus to two that are related to visual processing: Visual Attention Span (VAS) and the focusing of visual-spatial attention. There are a number of other common factors that have been examined including phonological processing skills, but these are not examined here.

Visual attention span (VAS)

VAS is hypothesized to be the number of orthographic units that are processed in one glance (Valdois et al., 2004). With very early readers this is generally assumed to be the number of letters but the parallel processing of letters, letter clusters and syllables has also been suggested to affect reading development at later stages (Vidyasagar & Pammer, 2010). A large VAS is indicative of words being processed through what is commonly referred to as sight reading, which in our model means that they are largely processed by the lexical route. Such that in this case, strings are processed in parallel, rather than serially through the sublexical part of the model.

However, the extent to which large groups of letters are processed in parallel is likely to be related to reading skill. Developing readers with a small VAS are required to focus upon the sublexical units of a word, thus, decoding the word with the support of serial sublexical process (Ans et al., 1998). Most commonly, VAS is measured through tasks that involve processing of meaningless material with no lexical processing or linguistic skills required, for example consonant, digit or shape strings (Valdois et al., 2003; Valdois et al., 2012; Lobier et al., 2012; Lobier et al., 2013). Thus, VAS reflects how attention is distributed over a string of letters when reading, in order to modulate letter identity processing (Valdois et al., 2019). For example, Lobier et al. (2013), presented individuals with letter stings, and asked them to verbally recall as many letters as possible. The strings of letters never contained repeat letters and never matched real English words. Lobier et al. (2013) established that in this experimentation VAS predicted reading accuracy and speed, and was found to be independent of an individual's phonological skills and verbal short-term memory.

Van den Boer and de Jong (2018) ascertained that VAS predicts reading performance above phonological skill, for both children with dyslexia and without. A deficit in the visual attention span is the most prominent attention theory explaining dyslexia, and has been proposed by Valdois and colleagues (Valdois et al., 2004; Bosse et al., 2007; Valdois et al., 2012). In their theory, typical readers have a higher VAS than poorly developing ones. This enables them to process more letters per glance when reading, thus make fewer fixations. Length effects are the processing speed of a visual word and the correlation with its length, with most studies focusing upon increasing numbers of letters. Greater length effects have been reported amongst the dyslexic population with deficits in VAS (Barton et al., 2014). This highlights that enhanced letter identification requires higher visual attention capacity. Processing of whole letter strings in longer orthographic units leads to a higher probability of accurate parallel processing, allowing for more fluent reading. Furthermore, it is suggested that when reading irregular words, one's ability to process more word-letter strings is indicative of enough attention being allocated to all of the letters simultaneously. Hence, in line with Valdois et al. (2003), irregular word reading should be more sensitive to the available VAS for parallel processing. That is, the ability children have to read words such as *aisle*, which can only be read by processing all the letters at once, will be more strongly related to VAS than words which can be processed piecemeal. Bosse and Valdois (2009) further highlight that as VAS increases as children learn to read better, irregular word reading performance increased. Valdois et al. (2019) also found that among children with dyslexia, a deficit in VAS led to poor reading accuracy and slow reading speeds, for all types of words and irrespective of their phonological skill.

Focused visual-spatial attention

Focused visual-spatial attention is well known for enhancing visual processing. With respect to reading, this involves directing and orientating one's attentional focus to attend to segments during word reading (Facoetti et al., 2006). Perry et al. (2007) ascertain that focused visual-spatial attention is employed in the conversion of phonology from printed words, through the graphemic parsing process that can be seen in Figure 1. Graphemic parsing requires a shift in the focused spatial attention of an individual and consequently is an attention demanding process. For reading, this type of attention is particularly important as it enhances visual processing. This can be reflected in not only processing speed, but also sensitivity to reading stimuli and reduced interaction with stimuli nearby.

Facoetti et al., (2006) have linked nonword reading performance (i.e., reading word-like sequences of letters that are not actual words, e.g., *splorf*) to focused visual-spatial attention, namely in developmental dyslexia. They found that reaction time speeds in orientating attention tasks were seen to account for a large proportion of variance amongst this population all whilst controlling for age effects, IQ and phonological skills. Similarly, Buchholz and Davies (2005) came to the same conclusion that dyslexic individuals have difficulties in shifting their attention exogenously between objects. Furthering this research, Roach and Hogben (2008) found when dyslexic adults were briefly presented with spatial cues, they were unable to take advantage of them in order to improve their performance in the direction discrimination of a target. This research again establishes that individuals that have a poor ability to use focused visual-spatial attention will also have trouble with orienting and directing their attention needed during reading.

A very well-utilized spatial orienting task is the Posner task (Lundwall et al., 2018). This task manipulates the predictive validity of a spatial cue. Reaction times for a target detection are compared to reaction times of a manipulated cue condition (Posner, 1980). A cue can be endogenous (these are symbolic cues, that require a deliberate attentional shift from an individual) or exogenous (these are peripheral cues, thus drawing participant attention automatically). With the exogenous cues, individuals have faster reaction times to trials that have a valid cue than to a neutral trial. Conversely, in this exogenously cued task, individuals should display slower reaction times when shown invalid cues compared to neutral cues. Hence, these differences in reaction time between a valid and an invalid trial are indications of orientating effects, establishing the effectiveness of attentional shifting in individuals with certain cues (Roach & Hogben, 2008). Given this task is well accepted and simple for participants, we will examine its performance with reading below rather than use other more complicated orienting tasks which exist (e.g. spatial probe experiments such as visual search tasks (Prinzmetal et al., 1986)).

Summary

How visuo-spatial attention is used when reading for typical adults remains contentious. Simple correlations between aspects of attention and reading performance have been found by some, but they have not directly tested the possible effect on underlying reading mechanisms (Facoetti et al., 2019). Elucidating this further is important because the way factors that affect how reading works may be used to help understand dyslexia, as well as predict likely outcomes from different types of training programs. It is also useful in terms of model falsification, as some current models of reading make predictions about how it should affect reading (Perry et al., 2013). This will be investigated by measuring and manipulating visuo-spatial attention and examining its effect on the reading aloud of words and nonwords.

Predictions

Prediction One

Based on the CDP++ model, we know that whenever people read, they typically use both lexical and sublexical procedures – one does not simply switch one off. We also know that this causes irregular words to be processed more slowly as conflict between the correct lexically derived pronunciation is resolved with the incorrect pronunciation derived from the sublexical route (e.g. producing *pint* to rhyme with *mint*). We therefore predict that those with a good performance on a VAS task will read irregular words better in terms of speed and accuracy than regular ones.

Prediction two

A second prediction we can make is that because nonwords are read in a small chunks, those good at a VAS task should not be better at nonwords processing, but they may be better at processing words *compared to* nonwords.

Prediction Three

We hypothesize that those who show a large orienting effect will be faster at processing nonwords than those who show a weak orienting effect, and in particular show weaker length effects because they will be able to process the smaller letter groupings faster.

Overall Predictions

Overall, we are interested in whether two different types of attention can be dissociated on different aspects of reading.

Method

Participants

Twenty-seven participants were recruited for this study. Exclusion criteria for this study comprised of not being a native English speaker or having a known reading disorder. Participants were aged between 17 and 78 (M=33) and were female 63.0% and 37.0% male.

The sample consisted of seven first year University of Adelaide students and 20 convenience sampled participants. University of Adelaide students were recruited through the university's Research Participation System, SONAR. For participating in this study the students were credited with 1 towards their university research participation hours. Convenience sampled participants were not compensated in any way.

Outline and Procedure

Firstly, a simple reading aloud task asked participants to read a list of words and nonwords aloud into a microphone, to examine the reaction time speed and responses to them. Secondly, visual attention was measured using the visual attention span task as described above, which is similar to that used by Lobier et al., (2013). The results from this can be correlated with results from the reading task. This allowed the effects of visual attention span to be examined as well as the effect of stimulus difficulty, and thus potential interactions between these measures. Lastly, we ran the focused visuo-spatial attention task, this was measured via an experimental manipulation designed to interfere with the left-to-right focusing of attention, using distractor stimuli that make this difficult.

Participants undertook three tasks sequentially: the reading task, the visual-attention span task, and the Posner task. There was a two-minute break between each task, where participants were verbally told the instructions for the next task.

We performed a variety of quantitative statistical tests upon the collected data, including Analysis of Variance (ANOVA) and Pearson's correlation analysis. In all cases we used an alpha level of .05. Furthermore, we did not perform a sample size estimation as we were undertaking a pilot study. A number of post hoc corrections were applied but have not necessarily accounted for multiple comparisons.

Materials

The experiment was carried out with a 69cm screen located 60cm away from the participants. The LG 27MP59G-P screen had a resolution of 1920 x 1080 pixels and a 100Hz refresh rate. Two screens were used: one as an operation screen from which the experiment controlled, and the other for the participant where the tasks were displayed with the outlined specifications. Participants responded either on a keyboard or into a microphone that was placed 5cm away from their mouth depending on the task being executed.

Reading Task

Participants were asked to read 250 words on a screen as quickly and accurately as possible. The first 10 words were used as fillers for the participant to practice on and the other 240 words acted as the experimental set. Of the 240 experimental words, half were nonsense-words (i.e., words that sound real but do not exist, e.g., *blipe*, which we will refer to as *nonwords*), and the other 120 words part of the English lexicon (Appendix A).

The 120 words were broken down into four groups based on two factors that created a 2 by 2 design. The two factors were spelling-sound consistency and letter length. Spelling-sound consistency statistics were taken from Perry et al. (2010). They represent a metric that pertains the extent to which a word has spelling-sound relationships that are commonly used or atypical. For example, '*plaid'* has an inconsistent spelling-sound relationship whereas *'shelf'* only has consistent ones. Words which have only typical spelling-sound relationships are called consistent, whereas words than have at least one atypical relationship are called inconsistent. Whilst consistency is measured across a continuum, our experimental design was dichotomized into two groups and stimuli were selected from the extreme ends. Letter length is simply how many letters a word has. For example, *cat* has three letters and *catapult* has 8. The stimuli in the length manipulation were divided into two groups, long and short. The stimuli in the short group tended to be monosyllabic whereas the stimuli in the long group were disyllabic. Across the 4 groups, the words were balanced on onset phoneme and other lexico-statistics that were taken from Balota et al. (2007) from the *English Lexicon Project* (ELP; Balota et al., 2007) and are presented in Table 1.

The 120 nonwords can be broken into 6 groups of 20 words that were 4-8 letters in length. Nonwords that were 4-5 letters long were monosyllabic (*'bipe'*) and those that were 7 or 8 letters were disyllabic (*'vouseful'*). There were two 5 letter nonword groups. In one of the groups they were monosyllabic and in the other group they were disyllabic. The groups of twenty were balanced on onset phonemes across the groups.

Table 1

Means and Standard Deviations and Mean Accuracy Taken From ELP, Balota et al. (2007) Speed Naming Task.

	Mean Reaction time (ms)	Standard deviation (ms)	Mean Accuracy
Monosyllable consistent spelling-sound relationship	628.36	136.02	0.99
Disyllable consistent spelling-sound relationship	650.56	136.13	0.99
Monosyllable inconsistent spelling-sound relationship	653.76	135.32	0.91
Disyllable inconsistent spelling-sound relationship	718.16	178.25	0.96

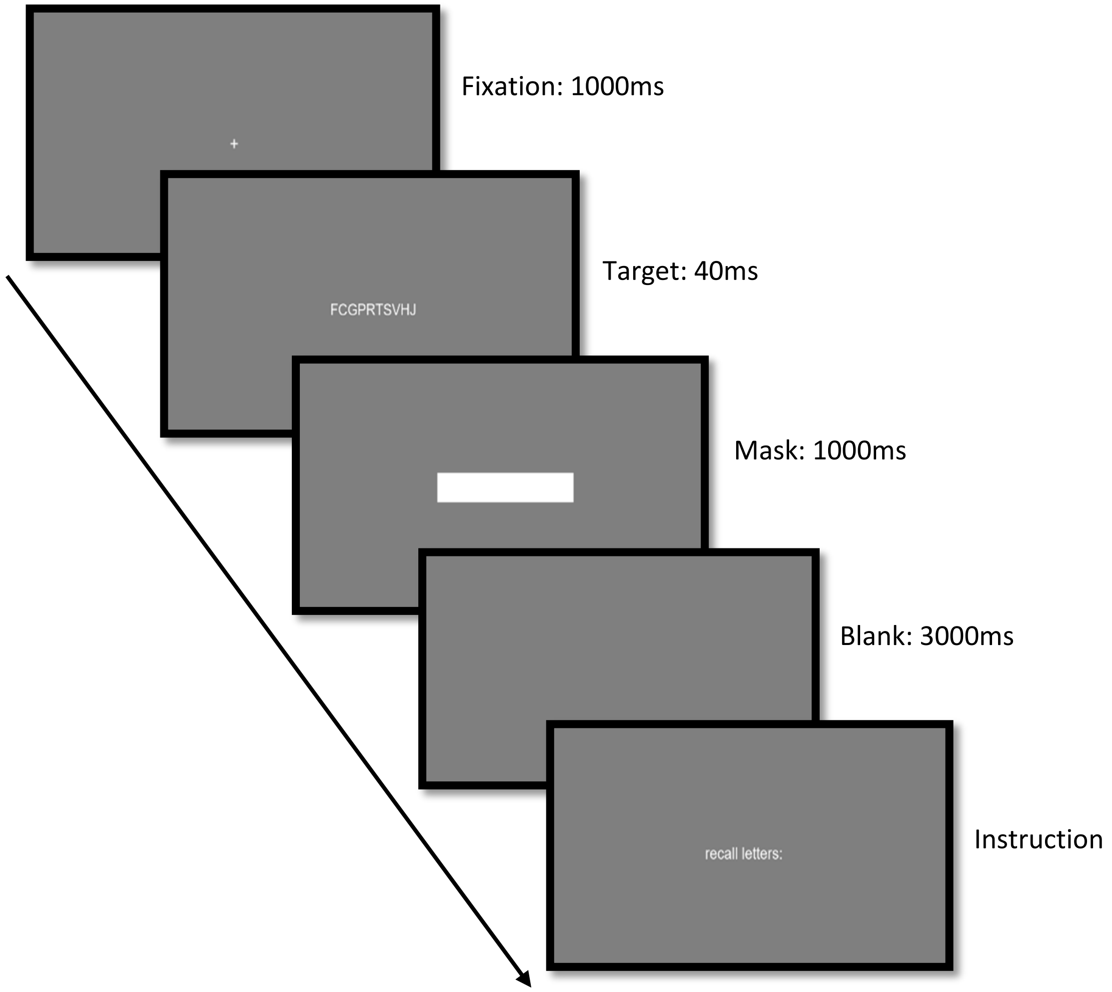
For the aforementioned reading task, words were presented in a 16-point font in the centre of the screen. Participants were recorded speaking the words into a microphone. The words and nonwords described above were present in a randomised order after the first 10 filler words. During this task, the participants were monitored for speech errors, such as pronouncing *pint* to rhyme with *mint*.

Visual-Attention Span Task

Participants used the visual attention span (VAS) task as described by Lobier et al. (2013) but which was modified so it was suitable for adults. Each trial followed the basic sequence as shown in Figure 3, where participants were asked to fixate upon a cross in the middle of a grey screen. Participants were shown a grey screen for 100ms before the stimuli were displayed. The stimuli consisted of 10 uppercase letters presented in size 16 in Geneva font. The 10 randomly chosen letters only contained consonants and had no duplicates. The string was placed such that the fixation cross was in the middle of the string, between the 6^{th} and 7^{th} letter with the edge of the first and last letter subtended at a 7-degree angle with a vertical distance of 1 cm and 0.57 degrees between each of the letters. These were displayed in a white font for 40ms. After that, a white box appeared on top of them for one second, as seen in Figure 3. A grey screen then appeared for half a second before participants were prompted with the words: “recall letters”, where the participant entered as many letters as they could recall via the keyboard. The number of letters correctly given was the number that they typed in that existed in the string, irrespective of the order. The task took participants around 10 minutes to complete and was comprised of 10 practice trials and 30 experimental trials presented in a randomised fashion. Participants were instructed not to guess their response and encouraged to keep their accuracy above 80%. They were also told that their reaction times would be irrelevant.

Figure 3

Sequence of Visual Attention Span Task With Duration of Each Stage of Task.

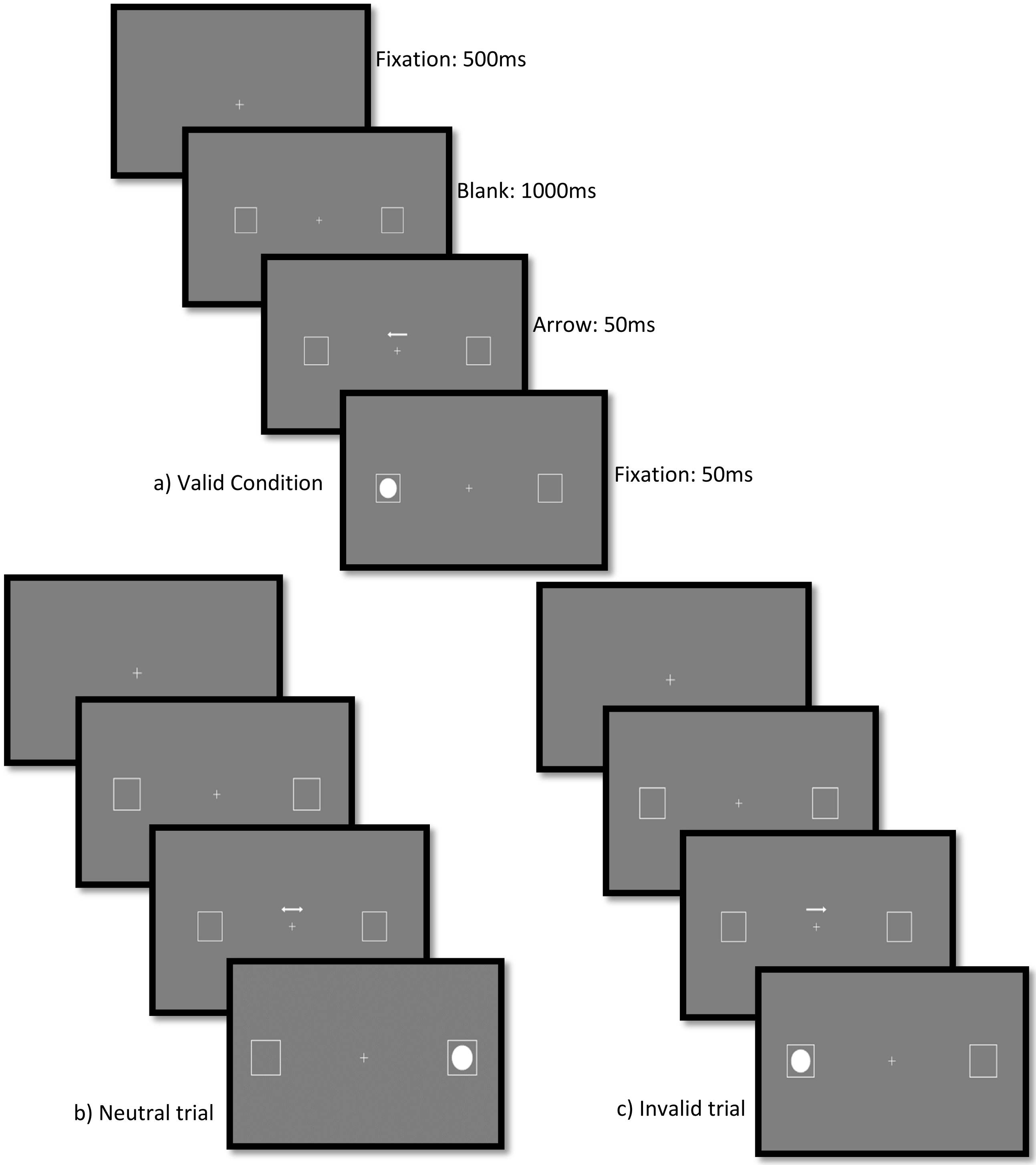


Posner Task

Participants were asked to complete a 15-minute task, which included 300 trials preceded by 60 fillers. This task is a variation of the Posner task (Posner, 1980), where individuals were presented with a central cross in the middle of the screen at eye level and asked to fixate upon this point. Participants were told that there would be two boxes, one on the right and one on the left, and that they should choose the box in which the circle occurred by pressing the ‘a’ key if it occurred in the left box or the ‘;’ if it occurred in the right box, as quickly and as accurately as possible. Additionally, an arrow appeared above the fixation cross and could either point to where the circle would appear (valid condition), point to the incorrect box (invalid trial), or be a double headed arrow, pointing both directions (neutral trial). The timing of the events, as seen in Figure 4, was as follows: that a) individuals fixated upon the cross for five seconds; b) blank boxes appeared for 1000ms; c) an arrow appeared for 50 ms; d) a circle appeared in one of the boxes for 50ms; and e) participants responded by pressing the ‘a’ or ‘;’ based on which box the circle was in. Of the trials presented to the participants, 66.7% were valid trials, 16.7% were invalid trials and 16.7% were neutral trials. The 60 fillers used the same proportions. The stimuli could be further divided based on whether the circle appeared in the left or right box. This was proportioned equal (50% in each box). Individuals were measured on how quickly they responded to the three different conditions.

Figure 4

Timings and Sequence of the Posner Trial. a) Indicating a Valid Trial Condition b) a Neutral Trial Condition c) an Invalid Trial Condition.



Results

Reading Task

Firstly, we cleaned the data. Two-hundred and ninety-seven data points were removed due to microphone errors (4.6%). These included the microphone potentially picking up a mouth noise before the word was said, an outside noise being picked up, or a cough or sneeze from the participant. Next, we removed 161 data points due to naming errors from the participant. This ranged from words being said incorrectly e.g., *pint* with the correct pronunciation of /paɪnt/ versus an incorrect /pɪnt/ (2.5%). A further 47 data points were then excluded due to being slower than a 1500ms response time cut-off (0.7%). Following this, we calculated a 3 standard deviation boundary for each participant. Thirty-six items were removed due to them being 3 standard deviations away from the mean: 29 for words and seven for nonwords (0.4% and 0.1% respectively).

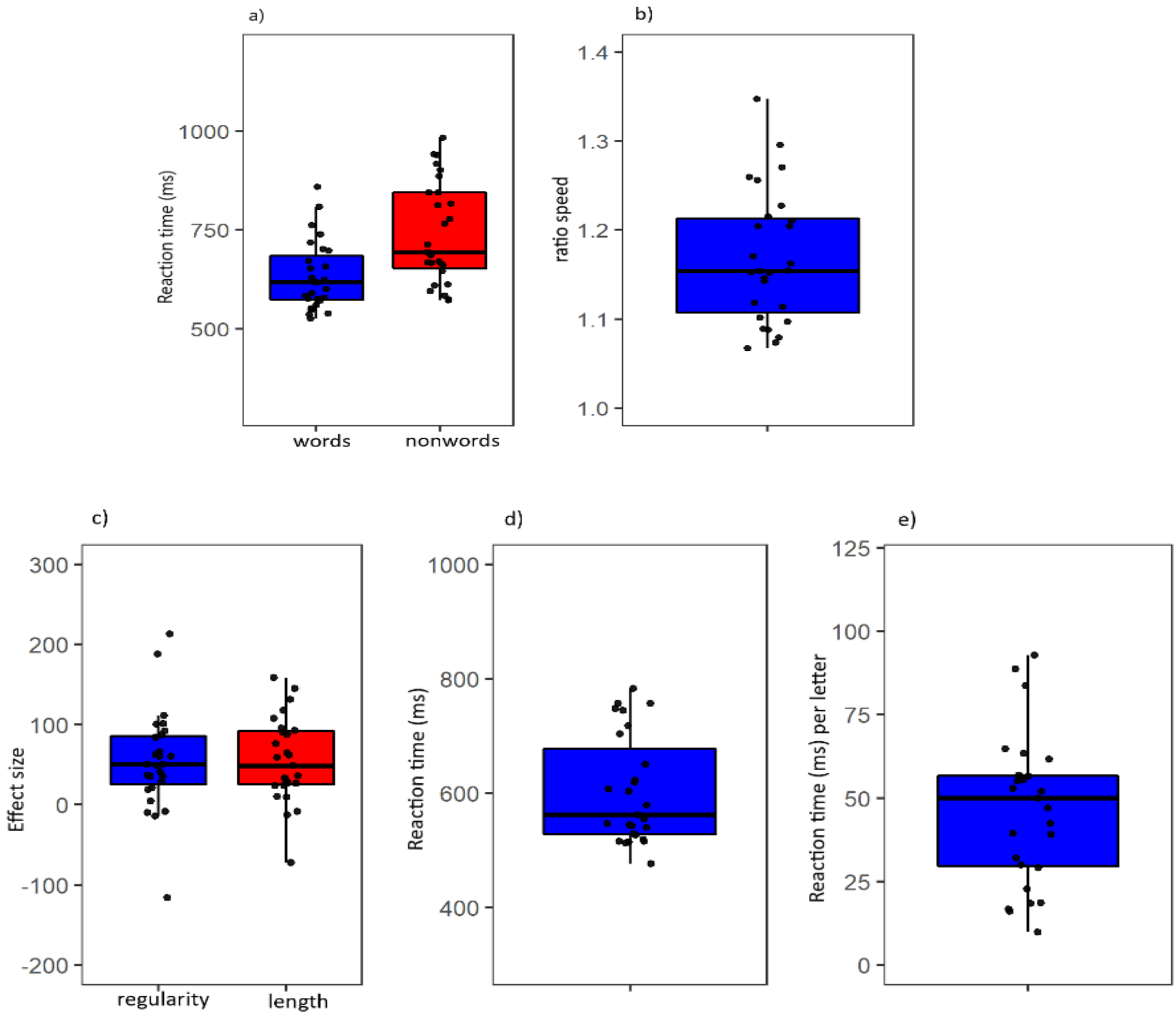
Rather than use a typical categorical design with the nonwords where the words are broken into groups based on their number of letters, we instead regressed letter length as onto reaction times. This was possible because the length effect for nonwords was very linear for each participant. This meant that, for each participant, we had a constant for overall reaction time and a beta value that represented the slope of the length effect.

On inspection of the data, we found that the two groups of five letter long nonwords (which were split into monosyllabic and disyllabic groups) had almost identical mean reaction times (743ms vs. 739ms). These were therefore collapsed into a single group. Next, we examined the distribution of individual responses on the different effects of interest below in Figure 5. These included the overall reaction times for both words and nonwords, the speed of nonwords compared to words as indicated by the nonword/word ratio, the size of the regularity and length effect in the words, the constant for nonwords and beta value for length.

As can be seen, most of the distributions looked reasonable and thus lay between the first and third quartiles, although there were potentially outliers with the regularity effect that were visually obvious and could also be identified statistically. Given these effects are known to differ widely across participants, we did not remove those who produced the larger effects, although we did check the analyses reported below with one outlier removed and it made no meaningful difference.

Figure 5

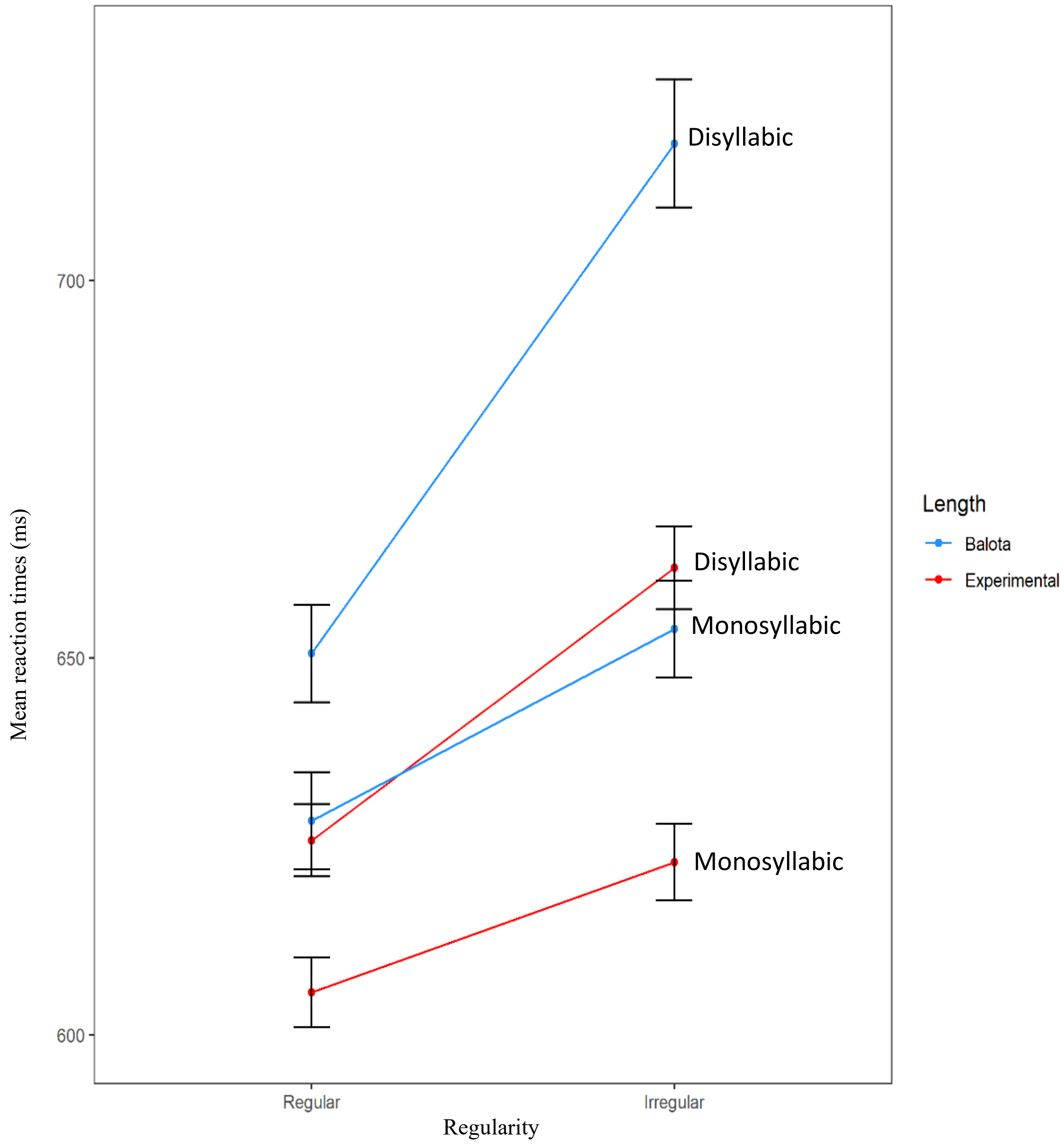
The Distribution of Responses on the Different Effects of Interest: a) Overall Reaction Times, b) Nonword to Word Reaction Time Ratio, c) Effect Sizes of Words With the Blue Box Indicating the Regularity Effect and the Red Box the Length Effect, d) Constant Reaction Time Derived From Nonwords and e) Letter Length Speed per Letter in Nonwords.



We next examined the words. The overall means from the reading task were similar to those from the Balota and Spieler (1999) database. Although our participants had overall faster reaction times than those of the Balota database they were proportionally very similar. These appear in Figure 6.

Figure 6

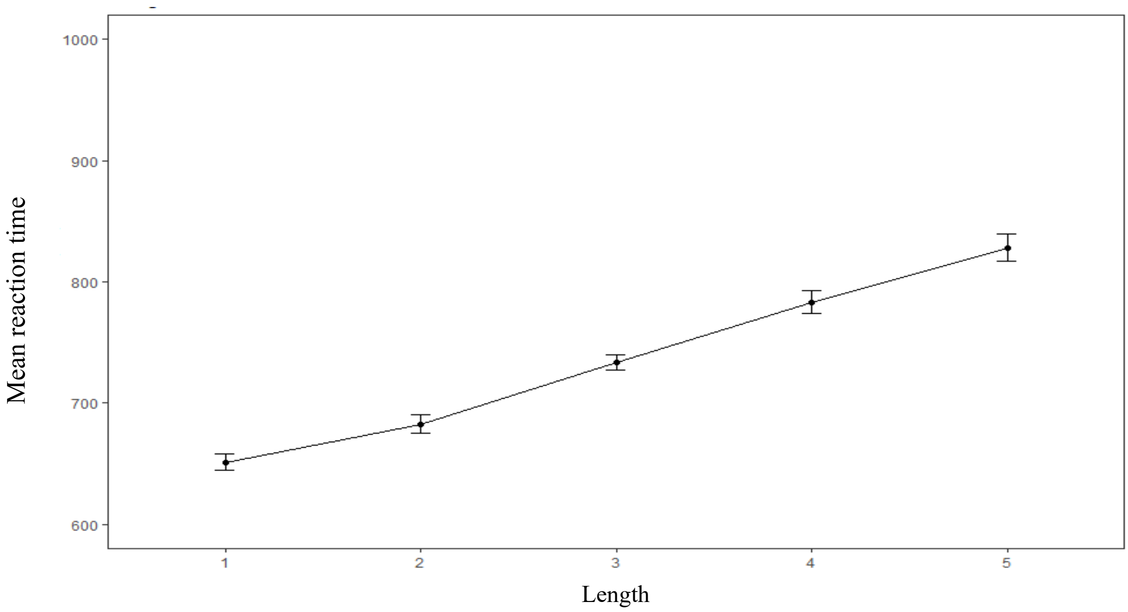
Overall Mean Results From the Word Reading Task for Balota and Spieler (1999) and our Experimental Data. Error Bars are +/- 1SE.



To examine the reaction time results from the reading task, we used a linear mixed model using regularity and length as both random and fixed factors, with slopes for the random factors added for both participants and items, and the interaction terms as a fixed effect factor. The results showed only a significant effect of length $F(1, 71.37) = 5.66$, $p = .020$ (note that effect size cannot be estimated accurately for mixed effects models). Next we examined the nonwords, also using a linear mixed model with length as both as random and fixed factors, with random slopes for participants and items. These showed a strong length effect, $F(1, 63.35) = 68.99$, $p < .001$, As can be seen in Figure 7, as the length of the word increases so does the mean reaction time.

Figure 7

The Mean Response Times Plotted Against the Length of Nonwords Presented to Participants.



As shown in Table 2, we also examined simple Pearson correlations between overall word speed, overall nonword speed, regularity, length, regularity, length, ratio of word/nonword speed, and the beta and constant from nonwords.

Table 2

Simple Pearson Correlation Coefficients Between Variables of Interest for the Reading Task

Variable	1	2	3	4	5	6	7	8
1. Overall word speed	—							
2. Overall nonword speed	.94***	—						
3. Regularity	.31	.18	—					
4. Length	.03	.13	-.11	—				
5. Regularity by length	.37	.38	.55**	-.10	—			
6. Ratio of speed	.45*	.72***	-.14	.27	.28	—		
7. Nonword beta	.60**	.70***	-.13	.23	.28	.66***	—	
8. Nonword constant	.86***	.86***	.33	.02	.32	.52**	.25	—

*p<.05. **p<.01. ***p<.001.

Note. Regularity is indicative of if a word from the English lexicon having an irregular or regular pronunciation. Length denotes if the word is mono or disyllabic. Regularity by length is combining these factors mentioned above. Ratio of speed indicates Nonword reaction times divided by the word reaction times for each participant. Nonword beta is representative of how much more slowly individuals processed long words than short words. Whereas Nonword constant, is the overall reaction time for nonwords before accounting for length.

Not surprisingly those who were slower at reading also produced larger regularity with words and length effects with both words and nonwords. This relationship has been documented many times (Barton et al., 2014; Adelman et al., 2010; Cohen et al., 2008; Weekes, 1997). Thus, not only does our data replicate Balota and Spieler (1999), but the inter-individual correlations are also similar to other studies. It thus seems reasonable to conclude therefore that there is nothing especially atypical about our data set.

Posner Task

We first examined each individual from the Posner task. One had a very high percentage of slow responses, with 6% of responses greater than 900ms. Given this and given we did not have an eye-tracker to monitor the participant, this participant was discarded.

Next, we removed all items that had incorrect responses, this removed 1.12% of the data. Further, we removed all items that had response times greater than 900ms. This removed 0.83% of the data. Following this, we used a 3SD cut-off for each group. This removed 1.85%, 1.15% and 1.23% of the data for the valid (n=200), invalid (n=50), and neutral (n=50) trials respectively. Inspection of the data showed that the mean results for the circles that appeared in the left and right boxes were almost identical. We therefore collapsed the data on that variable. The mean results are shown in Table 3.

Table 3

The Mean Reaction Times in the Valid, Invalid, and Neutral Conditions (ms).

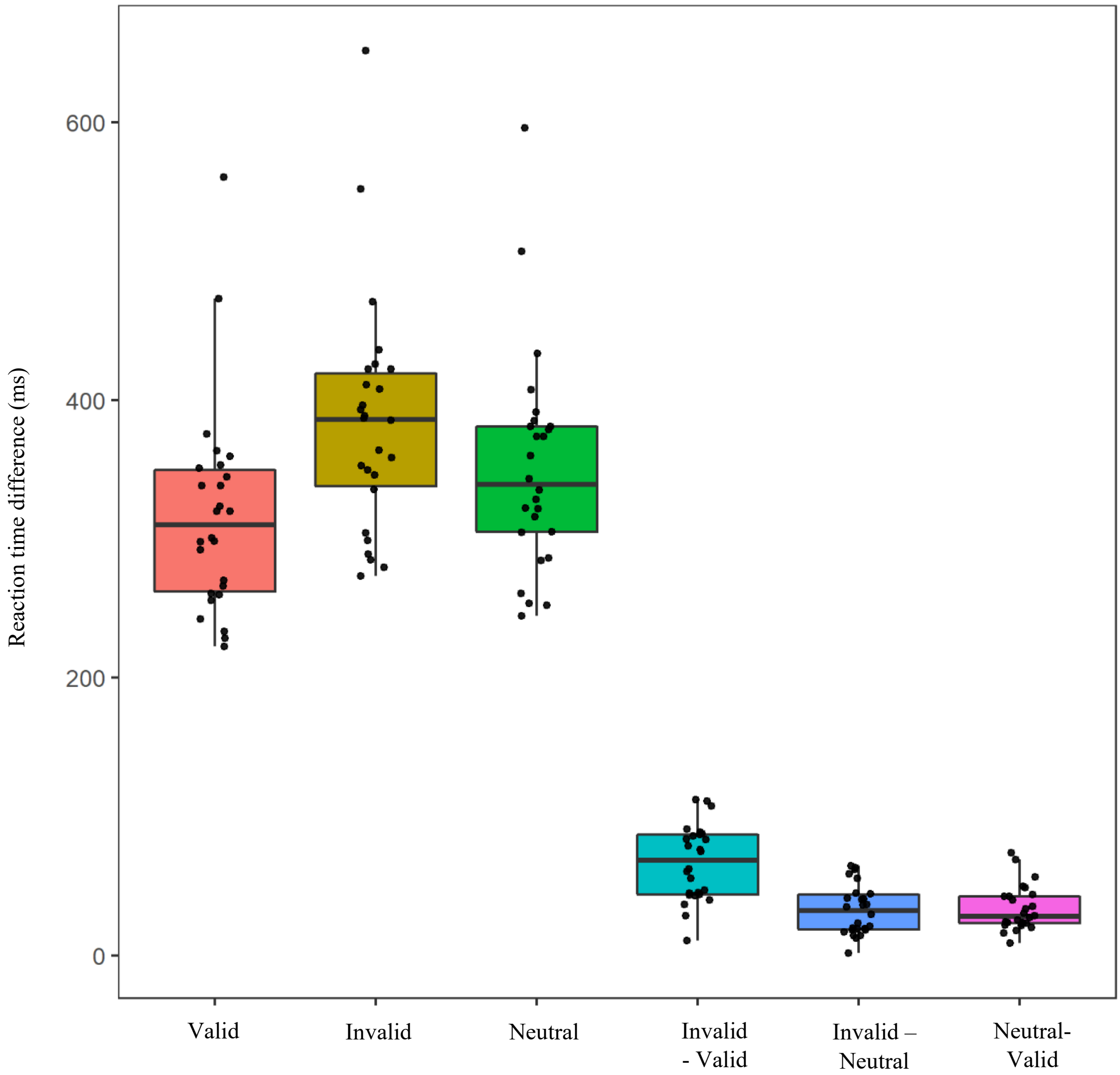
	n	*Left mean*	*Right mean*	*Total mean*	*Total SD*
Valid	100	320	320	320	75
Invalid	50	390	380	380	85
Neutral	50	360	340	350	79

We next inspected the individual scores on the task, and difference scores that were created by subtracting the valid scores from the invalid scores, the neutral scores from the invalid ones, and the valid scores from the neutral ones.

As can be seen in Figure 8, there were two participants that were especially slow at the task. However, their difference scores were within the normal range. In addition, leaving these two participants in the analyses made little difference to the overall results as seen in the mean difference and statistical comparisons. Therefore, they were retained.

Figure 8

Boxplot of Individual Participant Scores for the Valid, Invalid and Neutral Trials as Well as Differences Between Invalid-Valid, Invalid-Neutral and Neutral-Valid Trials.



We next performed a one-way analysis of variance. The results showed a main effect of the group (Valid, Invalid, Neutral) that was significant, $F(2, 52)$ 97.06, $p < .001$, $\eta^2 = .79$.

Further post-hoc analyses revealed all were significantly different from each other (p values< .001).

Following this, we examined correlations between the different conditions. Unsurprisingly, the overall scores from the three groups were very strongly correlated for the single groups (Table 4). For the difference groups, a mixture was obtained with some highly significant while others were non-significant.

Table 4

Correlations Between Each Valid, Invalid and Neutral Trial Group in Addition to the Difference Groups.

Group	*1*	*2*	*3*	*4*	*5*	*6*
1. Valid	—					
2. Invalid	.95***	—				
3. Neutral	.98***	.98***	—			
4. Invalid-Valid	.19	.49*	.34	—		
5. Invalid- Neutral	.17	.41*	.21	.82***	—	
6. Neutral - Valid	.14	.37	.34	.77***	.26	—

**p<.05 **p<.01 ***p<.001*

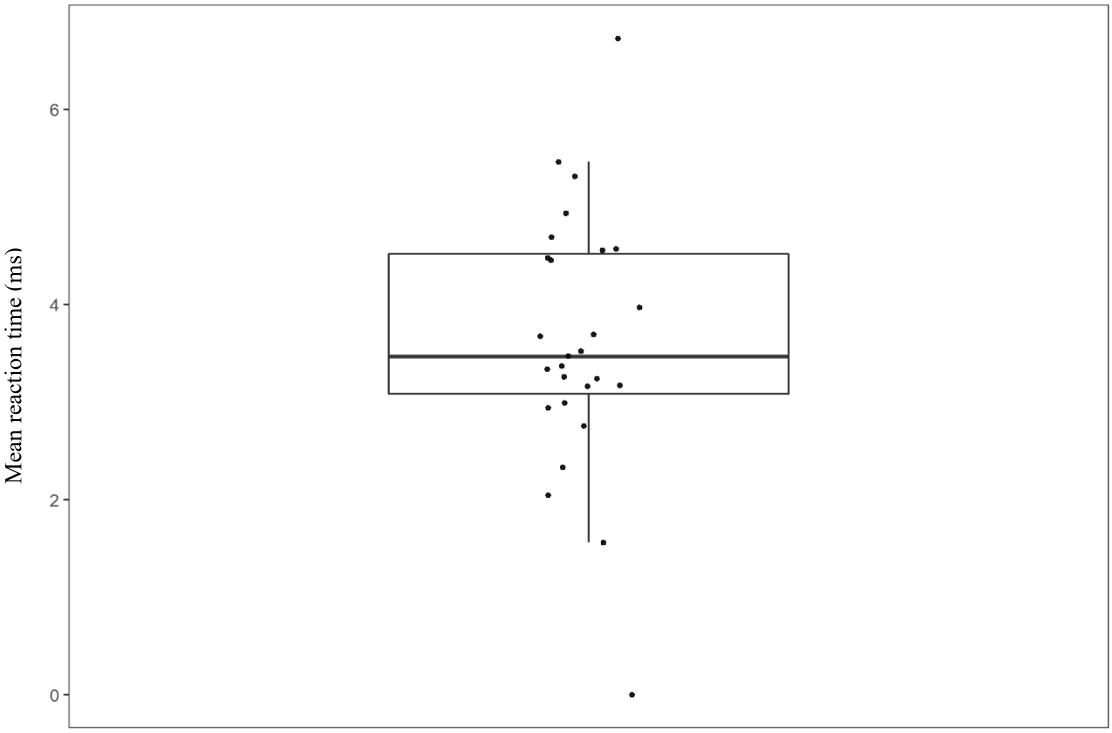
VAS Task

First, we examined the individual performance on the VAS task. As can be seen in Figure 9, there was quite a mixed distribution of responses. One participant scored zero on this task, thus was removed.

We also examined performance as a function of letter position, as displayed in Figure 10. As can be seen, the earlier letters to the left of the fixation cross, which appeared after the sixth letter position, were recalled with higher accuracy than those to the right of the fixation cross. However, the first letter was clearly quite different to the other letters. A phenomenon that gives special status to the letter in the first position in lexical processing is well known (Scaltritti & Balota, 2013) and for left-to-right reading it has been suggested that this occurs due to the receptive field being elongated to the left direction (Tydgat & Grainger, 2009).

Figure 9

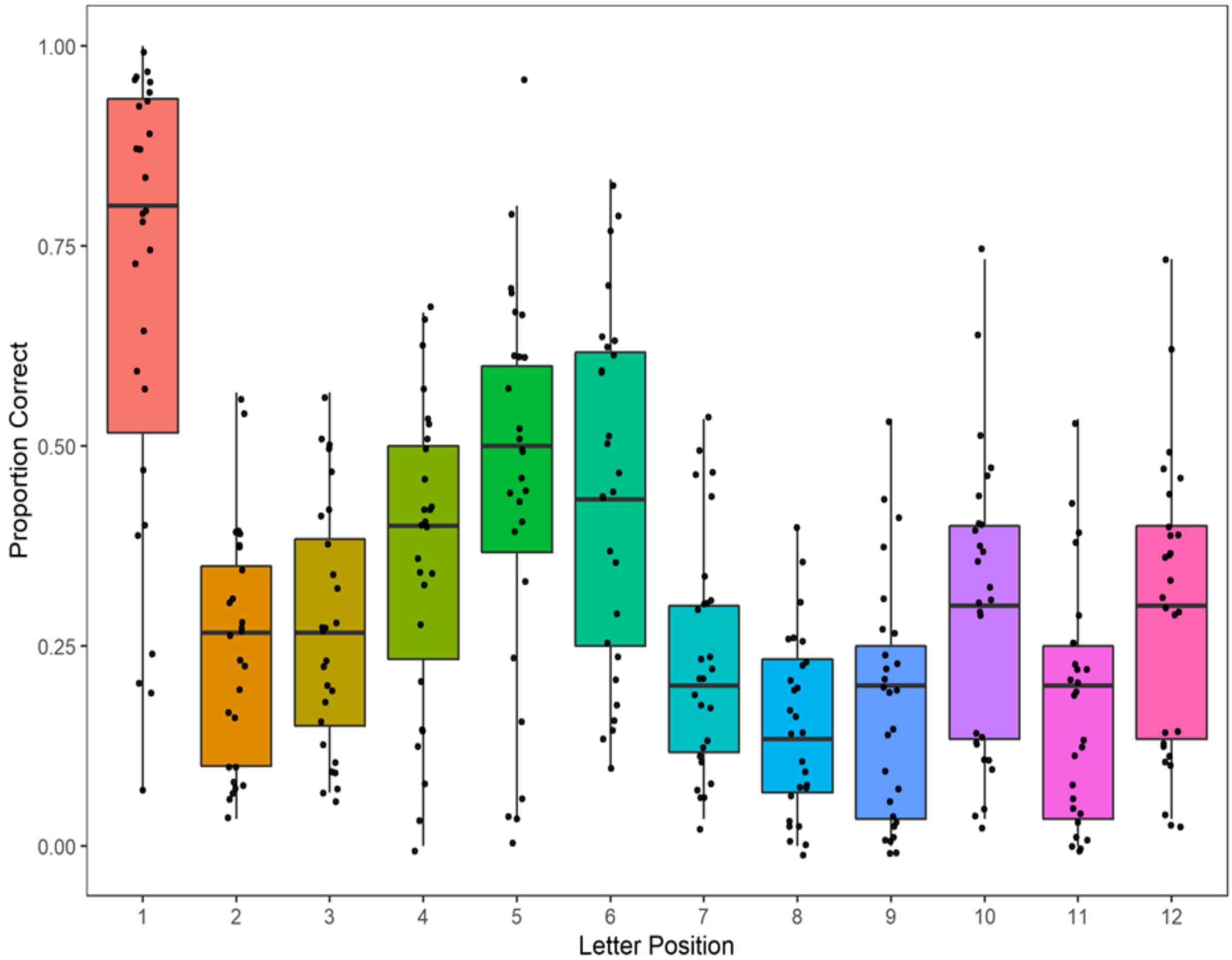
Participant's Aggregate Letter Position Scores.



Given the lack of any interfering character to the left, this optimizes the processing of the letters occurring in the initial position creating an advantage for reading the first letter. Given this and given this letter may be processed qualitatively differently from the rest, we calculated the total score without this letter. Further inspection of the individual data showed that there were a number of individual differences. Notably when ignoring the first letter, some participants tended to show a peak on early letters, and some did not; as displayed in Figure 11. The individual results are also interesting because they suggest some participants may allocate attention differently to others. Notably, as can be seen, some proportion of participants display higher accuracy to the left of fixation, but others do not. To examine this

Figure 10

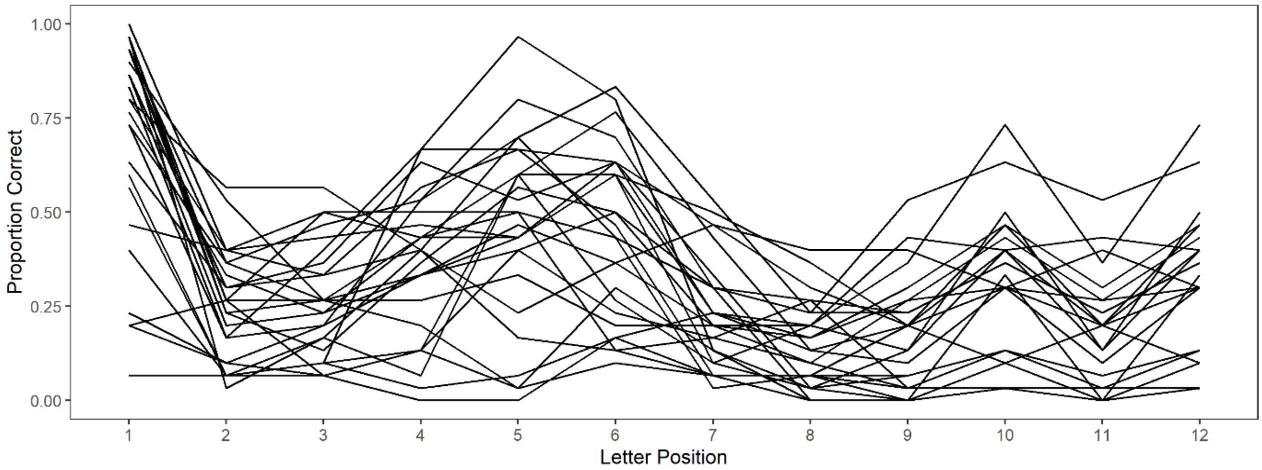
Individual Results Showing the Proportion of Correct Responses as a Function of Letter Position Effect Within the Visual Attention Span Task.



further, we fit a polynomial effect model with both a linear component and quadratic component on all letter positions, apart from the first. We then used one minus the p-score to measure the extent to which participants displayed a linear or quadratic effect. This meaning that a linear score close to one notes a small linear effect.

Figure 11

Letter Position in the Visual Attention Span Task Plotted Against the Proportion of Correct Responses.



Next, we examined the within-task correlations on these measures. As can be seen in Table 5, it was not the case that overall scores were predicted well by either the strength of the linear or polynomial effects.

Table 5

Pearson Correlations Coefficients of Linear and Polynomial Effects With the VAS Task.

	1	*2*	*3*
1. VAS score	—		
2. Linear effects	-.27	—	
3. Polynomial effects	-.30	.26	—

Overall Analysis

We first examined the relationship between our two non-reading tasks, the VAS and Posner tasks. As can be seen in Table 6, those who show a linear effect also tend to be slower at the Posner task and show larger difference scores. Alternatively, there were weaker effects for overall performance with the VAS scores. These results are interesting because it suggests that people who can distribute their spatial attention more evenly across a larger array of letters tend to be not only faster at the Posner task but also show less effects of expectations.

Table 6

Pearson Correlations of Posner Task With the VAS Task, Linear, Polynomial Effects, and VAS Score.

	VAS task		
Posner	Linear	Polynomial	VAS score
Valid trial	-.18	.12	-.37
Invalid trial	-.29	.20	-.31
Neutral trial	-.25	.18	-.33
Invalid versus valid	-.42*	.11	.17
Invalid versus neutral	-.35	-.08	.16
Neutral versus valid	-.41	.20	.18

**p<.05*

Next, we examined the reading task and the VAS task and variables likely to affect them (Table 7). The only variable which correlated significantly with the VAS data was the nonword/word speed ratio $r(23) = -.49$, $p=.016$. Thus, the higher the VAS score, the lower this ratio. That is, those that had a higher VAS score tended to also have a smaller discrepancy between the speed at which they read nonwords and words.

Table 7

Pearson Correlations of the Reading Task With the VAS Task, Linear, Polynomial Effects, and VAS Score

	VAS task		
Reading task	Linear	Polynomial	VAS score
Overall word speed	.06	.21	-.14
Overall nonword speed	.11	.24	-.29
Regularity	-.21	.25	-.03
Length	.03	.07	-.36
Regularity by length	.02	.23	-.09
Ratio of speed	.15	.23	-.49*
Beta	.22	.24	-.22
Constant	-.01	.15	-.24

Next, we examined the correlations between the reading task and the Posner task as displayed in Table 8.

Table 8

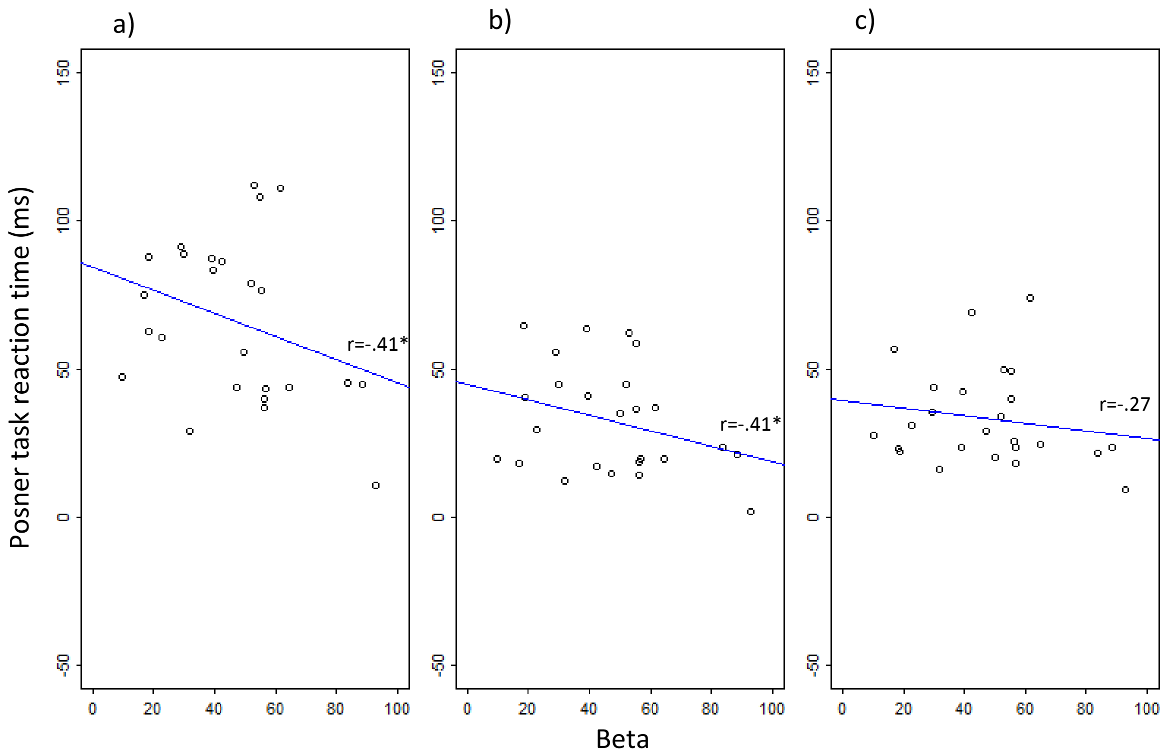
Pearson Correlations of Reading Task Areas of Interest With the Posner Task.

	Posner task					
Reading task	Valid	Invalid	Neutral	Invalid vs. Valid	Invalid vs. Neutral	Neutral vs. Valid
Overall word speed	.25	.22	.27	-.15	-.25	.04
Overall nonword speed	.22	.16	.22	-.21	-.27	-.05
Regularity	.20	.22	.26	.08	-.07	.22
Length	.07	-.02	.03	-.33	-.36	-.23
Regularity by length	.08	.01	.06	-.22	-.25	-.14
Ratio of speed	.06	-.01	.02	-.20	-.15	-.17
Constant	.35	.35	.37	.00	-.09	.13

As can be seen in Figure 12 there was a significant effect with invalid vs. valid trial. This indicates that individuals who showed a smaller length effect were also likely to show a larger between-conditions difference on the Posner task.

Figure 12

The Relationship Between Reaction Time Differences From the Posner Task Reaction Times and Overall Nonword Length Effect as Indicated by the Beta Value a) Invalid vs. Valid Trial, b) Invalid vs Neutral Condition and c) Neutral vs. Valid Condition.



Discussion

Prediction One

Within the Connectionist Dual Process (CDP++) model, it has been established that both the lexical and sublexical procedures are used concurrently when reading. For our first prediction, we anticipated that this would be demonstrated by a correlation between good VAS task performance and better irregular word reading compared with regular word reading. In this case, the better one's score is for the VAS task, the more letters one can process in parallel. We assumed that people good at the VAS task would also be good at processing words that require a global context to be read aloud correctly, i.e., irregular words. Thus, we expected a negative correlation between VAS scores and reading speed with irregular words. Whilst we found a negative correlation (Table 7) between the regularity and the VAS score, it was small and non-significant. Consequently, at least with typical adult readers, a higher VAS does not appear to confer any meaningful processing advantage.

The VAS results are theoretically interesting. Previous research on the lexical route of the CDP++ had suggested that irregular words would require a larger visual attention span, although it is possible that our words were simply not long enough to differentiate between people. One alternative is that the smaller chunks are being read through the sublexical route, this causes irregular words to be processed more slowly with less accuracy. Whilst no meaningful processing advantages were found considering the higher VAS scores, there were interesting results when looking at the linear and polynomial effects calculated from the VAS task on regularity. In this case, we looked at people who tended to process small groups of letters better than others (polynomial effect) or tended to process most letters with similar accuracy (linear effect). Whilst the majority of correlations between the reading task and the linear and polynomial effects respectively were in the same direction, they were not significant. All but the regularity displayed positive correlations with the linear and polynomial effects. Thus, indicating the lower the strength of the linear and polynomial models, the slower the reaction times in the reading task. Regularity, however, showed a different effect. Linear effects correlated negatively with the regularity of the word whilst polynomial effects correlated positively, with a similar magnitude. Simplistically, the stronger the tendency to read in a scanning manner, the more slowly the participant read irregular words than regular words. The inverse was also true for the polynomial tendency of reading in optimal windows. A large optimal window, shown by a high VAS score, may allow the pronunciation provided by the lexical route to be resolved more quickly than the incorrect pronunciation produced by the two-layer associative network of the sublexical route (Figure 1). A lower VAS score allows the incorrect pronunciation developed by the combination of constituent phonemes processed by the sublexical route to win out.

Prediction Two

The second prediction that we made was that because nonwords are read using small chunks of letter, rather than with all letters at once, there should be no relationship between the VAS and nonword processing. As can be seen in Table 7, the relationship between VAS scores and nonword reading was not significant. Alternatively, we also predicted that that individuals may be better at processing words *compared to* nonwords if they had a high VAS score, as indicated by the speed ratio measure (nonword reading speed divided by word reading speed). As seen in Table 7, we did find a statistically significant negative correlation between the VAS score and the speed ratio. When we see a smaller speed ratio, this is indicative of a similar nonword to word reading speed. With respect to the CDP++ model, this suggests that the larger the VAS window, the more letters the lexical route is able to process in parallel. Such a result is consistent with the results of Valdois et al., (2003), who suggested that this function was related to the ability to allocate enough attention to all of the letters in a word simultaneously. This allocation of attention phenomenon is also seen in individuals with dyslexia, as found by Bosse & Valdois (2009).

The VAS task by itself showed an interesting effect: that the initial letter had a much higher accuracy than other letters, as can be seen by the first letter phenomenon displayed in Figure 5. Whilst this has been documented before, Scaltritti & Balota (2013) have suggested that this is important for the mapping of orthography to the phonology of a word, as the first letter is of functional importance for signposting the start of words in left-to-right alphabetic languages. When considering the CDP++ model, we can theorise that this is suggesting that the graphemic parser in the sublexical route is operating in a left-to-right manner, so the first letter position is a signpost of where it should start to impute the phonology of the word. This establishes that this letter may be processed qualitatively differently from the rest of the string, and that this finding can be tied to the serial processing of the CDP++ sublexical route.

There were also other non-linear effects in the data. For both word and nonword reading speed a stronger correlation was found with the polynomial effect as opposed to the linear model effects (Table 7), where letters to the left of the fixation were often read with comparatively high accuracy compared to other letters. This is interesting as the polynomial model is more indicative of the presence of an optimal attentional window distributed over a string of letters, and this has previously been suggested to be around the third to fifth letter in a word (Brysbaert & d'Ydewalle., 1991). The linear model is more indicative of a left to right scanning method of letter processing. Our score distribution on the VAS task notably showed that multiple participants display higher accuracy to the left of the fixation cross (Figure 11). This could explain why we obtained a higher correlation with the polynomial effect over the linear effect. In this case it may indicate that our participants were reading nonwords and words in less of a serial fashion and instead using a parallel processing of letter within an optimal window.

Prediction Three

With nonwords, we hypothesized that those who show a large orienting effect will be faster at processing nonwords than those who show a weak orienting effect. We felt this should be reflected in overall reaction times, but since many factors can affect these reaction times, it may be more likely to appear as something that effects the speed at which words are processed compared to nonwords. Our results showed that the Posner task did not significantly predict nonword reading speed. Thus, we were unable to demonstrate that this task directly links the ability to direct and orientate attentional focus to attend to segments during word reading, as Facoetti et al. (2006) has previously suggested.

One reason the Posner task may not have been a significant predictor of nonword reading is that the attention used in this task is not similar to that used in reading. In this respect, Perry et al. (2007) ascertained that focused visual-spatial attention is employed in the conversion of phonology from printed words through graphemic parsing processing. For reading, this type of attention is particularly important as it enhances visual processing. This includes not only processing speed, but also sensitivity to reading a stimulus. Increasing this sensitivity aids in reducing interaction with nearby stimuli, which ultimately could interfere in the attentional focus on the desired stimuli. However, this process is attentionally demanding as it requires shifts of focused spatial attention across a letter string. Alternatively, the Ponser task in this experiment may be failing to pick up this type of attention distribution which is hypothesized to occur when reading. In this respect, research conducted by O'Regan et al. (1984) suggests that fixation tended to be toward the beginning or the end of a word, and there was a significant asymmetry in the strength effect of the lexical processing. Thus, the location of the dictated fixation point greatly changes the time of fixation, with a 23 to 32 ms increase per letter reported. The linear and polynomial models fitted during the data process stage, demonstrated that people do this task differently, as can be seen in Figures 10 and 11. When a parabola-like binomial curve occurs, it is indicative of typical reading with the optimal viewing position. However, when this distribution is flat or linearly sloped, it is more like a typical visual span task where letters are read in a left to right sequential manner. If we extend this to the Posner task, we may be able to conclude that we are unable to use this task as a comparison to typical reading. This is because the way attention is distributed in this task may be quite different to typical reading. As O'Regan et al. (1984) suggests, providing a fixation point has methodological consequences for generalisability of perception experiments. As far as the efficiency of processing is concerned, for a provided fixation point provided in the centre of a word, this may not be comparable to the use of an identical fixation location with words of differing length and lexical structure.

Inspection of the results from the Posner task offers some evidence that attention usage is dissimilar to typical reading This can be seen in Table 3, where there was no significant differences in reaction times to the circle appearing on the left or right hand sides of the word. This is not predicted by any theory of attention in reading to do with small-unit processing or the initial processing of letters. We could suggest this is in agreement with Ziegler et al. (2010) who further pointed out that with VAS patterns of serial positions are different for atypical and typical populations. It was noted that, based on research by Tydgat & Grainger (2009), typical readers produced a "W" shaped patten where the greatest performance was seen at the central fixation point with a decrease in performance either side of this peak. However, as the W shape indicates, this performance recovers for the first and last letters or digits in the string. Collis et al. (2013) took this to suggest that this "W" shape is an indication that typical adult readers tend to spread their attention across the whole string. This line of thought can be seen in Figure 10, where a loose patten of a "W" can be visualised in the results obtained.

Overall Comments

Overall, we were interested in whether two different types of attention could be dissociated on different aspects of the CDP++ reading model. Whilst strong evidence was collected favouring distinct influence of VAS on the lexical route, there remain questions over the validity of the chosen tasks to measure the focused visual-spatial attention. In terms of relating this to possible effects on underlying reading mechanisms, the results are largely in agreement with at least the VAS literature, which suggests that those with smaller VAS tend to rely on the support of the serial sub-lexical process when decoding a word, which is congruent with previous work by Ans et al. (1998). When considering a central fixation but disregarding the first letter (of which the effects have previously been discussed), performance was highest close to the central fixation point, thus individuals attentional window could have a slight impact upon their nonword reading speed. This research demonstrated agreement with Bosse and Valdois's (2009) research that suggests as VAS increases, so does irregular word reading performance.

Apart from the VAS task, we discussed a possible explanation for some results, potentially due to the lack of validity of the Posner task in accurately measuring the type of attention used in reading. It is of note that the previous research, which hypothesised that nonword reading performance was linked to focused visual-spatial attention, was based on research using dyslexic individuals ((Buchholz & Davies, 2005); Facoetti et al., (2006); Roach and Hogben (2008)). Hence, the large proportion of variance amongst the population they found might not be seen amongst the typical population used in this experiment as we deliberately excluded individuals with any sort of reading disorder.

In addition, it may be that in *early* reading, the way attention is used by individuals with dyslexia is quite different to typical adult reading. Thus, processes which are initially important could be dropped as more efficient ones come online. Processes which explain significant variance may also become more automated in most people with typically developing reading, and thus are quantitatively less useful as predictors. As such, the conclusions reached using the Posner task may not extend to the typical population that we included here to test orienting effects predicted by the CDP++ model.

Limitations and Future Directions

Although the study assessed predictions as to how different types of attention could be dissociated on different aspects of the CDP++ model, there were nevertheless some limitations. The largest issue lies with the small total number of participants, and it would aid increasing confidence in obtaining clear conclusions if more participants were added. Unfortunately, due to a number of factors, including participants from a first-year student research pool showing up only irregularly, our sample was not as big as we had hoped. A factor in this irregularity could be the COVID-19 pandemic related restrictions and concerns, which may have influenced the update of this in-person experiment when there were other remote options available to them. Despite this, as seen in Figure 6, our mean reading results obtained the same trends as Balota et al. (2007), but the correlations were weaker than we had hoped.

A second limitation was that measurement errors were found that arose from, in particular, the microphone. Whilst the naming task used a small proportion of fillers, the errors could potentially could have been reduced by recording the data and calculating reaction times on sound files. However even this is not a fool-proof method, as it requires assumption on when articulation begins, which occurs before sound is emitted. Additionally, no eye tracker was used throughout the experiment, in particular, for the Posner task. Implementing this piece of equipment could allow for insight into potential reasons for unusually slow responses that were removed from the dataset. Using such an eye tracker in future experiments could aid in clarifying the results further.

Another limitation of the study that has previously been mentioned is the questions over the validity of the Posner task ability to accurately simulate the reading environment. Extending the study to include a control group along with individuals with atypical reading, such as dyslexic individuals, might give an indication as to if this task was able to pick up typical reading methods as opposed to atypical reading. If the same results are found with the atypical population, this might indicate a larger question regarding what, if any, part of the reading process the Posner task is picking up on. If the Posner task is not accurately modelling the focused visual attention processes, then it may be important to develop an alternate task.

The study could be further expanded to include other left-to-right read languages upon which the CDP++ model has been tested, such as French or German. This could be useful in identifying any areas of non-conformity between the languages, or alternatively help identify standard characteristics found in these left-to-right read languages that use the Latin alphabet. Building upon this, it would also be interesting to investigate the model for right-to-left languages (such as Arabic) as this was not encompassed by the current model. However, it would be interesting to investigate the difference in effects, if any, this directional difference would have on the visuo-spatial attention tasks. It is unlikely that this could be extended to include non-phonetic languages, as this model is predicated upon the existence of phonemes.

Conclusion

By testing the possible effects on underlying reading mechanism on the CDP++ model, this study aimed to determine the extent to which visuo-spatial attention is used when reading. Two tasks were used in order to manipulate visuo-spatial attention to establish their effects on a third task of reading words and nonwords aloud. Quantitative statistical methods were used to determine the relationships between the tasks, and by extension the manipulated visuo-spatial attention. Whilst not all our predictions were confirmed we did find a number of useful insights into how reading works. Most notably the results demonstrated that a wide attentional window allows pronunciation to be generated correctly by the lexical route compared with narrow attentional windows. A smaller VAS allows the incorrect pronunciation produced by the sublexical route's two-layer associative network to win out. The VAS task letter string used parallel processing as opposed to the serial processing of the sublexical route. Thus, a sensitivity of irregular word reading to the VAS available was found. Additionally, a smaller ratio speed correlated with a larger visual attention span task score. This seems to denote that the ability to process more sizeable orthographic units is linked with the fluency of one's reading.

Perhaps more importantly, we also found results that suggest the Posner task (one of the tasks which is commonly used to examine aspects of attention in reading) may suffer from validity issues in terms of it measuring the attentional systems that are used in typical reading. In future, tasks likely to better measure attention in reading with higher validity may help us understand the dissociation that has been reported in the literature.

Future research may be directed toward improving the validity of the testing used when testing the underlying mechanisms of the CDP++ model of reading aloud. This optimistically will be useful in terms of model falsification. Those with both typical and atypical reading patterns would benefit from this knowledge through its applications and incorporation into training methods and programs.

References

Adelman, J. S., Marquis, S. J., & Sabatos-DeVito, M. G. (2010). Letters in words are read simultaneously, not in left-to-right sequence. *Psychological Science*, *21*(12), 1799–1801. https://doi.org/10.1177/0956797610387442

Ans, B., Carbonnel, S., & Valdois, S. (1998). A connectionist Multiple-Trace Memory model for polysyllabic word reading. *Psychological Review*, *105*(4), 678–723. https://doi.org/10.1037/0033-295X.105.4.678-723

Balota, D. A., & Spieler, D. H. (1999). Word frequency, repetition, and lexicality effects in word recognition tasks: Beyond measures of central tendency. *Journal of Experimental Psychology: General*, *128*(1), 32–55. https://doi.org/10.1037/0096-3445.128.1.32

Barton, J. J. S., Hanif, H. M., Eklinder Björnström, L., & Hills, C. (2014). The word-length effect in reading: A review. *Cognitive Neuropsychology*, *31*(5–6), 378–412. https://doi.org/10.1080/02643294.2014.895314

Bosse, M. L., Tainturier, M. J., & Valdois, S. (2007). Developmental dyslexia: The visual attention span deficit hypothesis. *Cognition*, *104*(2), 198–230. https://doi.org/10.1016/j.cognition.2006.05.009

Bosse, M. L., & Valdois, S. (2009). Influence of the visual attention span on child reading performance: A cross-sectional study. *Journal of Research in Reading*, *32*(2), 230–253. https://doi.org/10.1111/j.1467-9817.2008.01387.x

Brysbaert, M., & d'Ydewalle, G. (1991). A mathematical-analysis of the convenient viewing position hypothesis and its components. *Oculomotor Control and Cognitive Processes*, 2, 331-340.

Buchholz, J., & Davies, A. A. (2005). Adults with dyslexia demonstrate space-based and object-based covert attention deficits: Shifting attention to the periphery and shifting attention between objects in the left visual field. *Brain and Cognition*, *57*(1), 30–34. https://doi.org/10.1016/j.bandc.2004.08.017

Castles, A., Rastle, K., & Nation, K. (2018). Ending the reading wars : Reading acquisition from novice to expert. *Psychological Science in the Public Interest*, *19*(1), 5–51. https://doi.org/10.1177/1529100618772271

Cohen, L., Dehaene, S., Vinckier, F., Jobert, A., & Montavont, A. (2008). Reading normal and degraded words: Contribution of the dorsal and ventral visual pathways. *NeuroImage*, *40*(1), 353–366. https://doi.org/10.1016/j.neuroimage.2007.11.036

Collis, N. L., Kohnen, S., & Kinoshita, S. (2013). The role of visual spatial attention in adult developmental dyslexia. *Quarterly Journal of Experimental Psychology*, *66*(2), 245–260. https://doi.org/10.1080/17470218.2012.705305

Facoetti, A., Franceschini, S., & Gori, S. (2019). Role of Visual Attention in Developmental Dyslexia. In L. Verhoeven, C. Perfetti, & K. Pugh (Eds.), Developmental Dyslexia across Languages and Writing Systems (pp. 307-326). Cambridge: Cambridge University Press. doi:10.1017/9781108553377.014

Facoetti, A., Zorzi, M., Cestnick, L., Lorusso, M. L., Molteni, M., Paganoni, P., Umiltà, C., & Mascetti, G. G. (2006). The relationship between visuo-spatial attention and nonword reading in developmental dyslexia. *Cognitive Neuropsychology*, *23*(6), 841–855. https://doi.org/10.1080/02643290500483090

Gough, P. B., & Hillinger, M. L. (1980). Learning to read : An unnatural act. *Bulletin of the Orton Society*, *30*(1), 179–196. https://doi.org/10.1007/BF02653717

Hulme, C., Nash, H. M., Gooch, D., Lervåg, A., & Snowling, M. J. (2015). The foundations of literacy development in children at familial risk of dyslexia. *Psychological Science*, *26*(12), 1877–1886. https://doi.org/10.1177/0956797615603702

Levy, B. A., & Lysynchuk, L. (1997). Beginning word recognition: Benefits of training by segmentation and whole word methods. *Scientific Studies of Reading*, *1*(4), 359–387. https://doi.org/10.1207/s1532799xssr0104_4

Lobier, M., Dubois, M., & Valdois, S. (2013). The role of visual processing speed in reading speed development. *PLoS ONE*, *8*(4), e58097. https://doi.org/10.1371/journal.pone.0058097

Lundwall, R. A., Woodruff, J., & Tolboe, S. P. (2018). RT slowing to valid cues on a reflexive attention task in children and young adults. *Frontiers in Psychology*, *9*, 1–15. https://doi.org/10.3389/fpsyg.2018.01324

Lyon, G. R., Shaywits, B. A, Shaywitz, S. E. (2003). Defining dyslexia, comorbidity, teachers' knowledge of language and reading: A definition of dyslexia. *Annals of Dyslexia*, *53*(1), 1–14. https://doi.org/10.1007/s11881-003-0001-9

McClelland, J. L., & Rumelhart, D. E. (1981). An interactive activation model of context effects in letter perception: Part 1. account of basic findings. *Psychological Review*, *88*(5), 375–407. https://doi.org/https://doi.org/10.1037/0033-295X.88.5.375

Morais, J., Cary, L., Alegria, J., & Bertelson, P. (1979). Does awareness of speech as a sequence of phones arise spontaneously? *Cognition*, *7*(4), 323–331. https://doi.org/10.1016/0010-0277(79)90020-9

Morton, J. (1969). Interaction of information in word recognition. *Psychological Review*, *76*(2), 165–178. https://doi.org/10.1037/h0027366

O'Regan, J. K., Lévy-Schoen, A., Pynte, J., & Brugaillière, B. (1984). Convenient fixation location within isolated words of different length and structure. *Journal of Experimental Psychology: Human Perception and Performance*, *10*(3), 250–257. https://doi.org/10.1037/0096-1523.10.3.393

Perry, C., Ziegler, J. C., & Zorzi, M. (2007). Nested incremental modeling in the development of computational theories : The CDP + model of reading aloud. *Psychological Review*, *114*(2), 273–315. https://doi.org/10.1037/0033-295X.114.2.273

Perry, C., Ziegler, J. C., & Zorzi, M. (2010). Beyond single syllables: Large-scale modeling of reading aloud with the Connectionist Dual Process (CDP++) model. *Cognitive Psychology*, *61*(2), 106–151. https://doi.org/10.1016/j.cogpsych.2010.04.001

Perry, C., Ziegler, J. C., & Zorzi, M. (2013). A computational and empirical investigation of graphemes in reading. *Cognitive Science*, *37*(5), 800–828. https://doi.org/10.1111/cogs.12030

Perry, C., Zorzi, M., & Ziegler, J. C. (2019). Understanding dyslexia through personalized large-scale computational models. *Psychological Science*, *30*(3), 386–395. https://doi.org/10.1177/0956797618823540

Peterson, R. L., & Pennington, B. F. (2012). Developmental dyslexia. *The Lancet*, *379*(9830), 1997–2007. https://doi.org/10.1016/S0140-6736(12)60198-6

Posner, M. I. (1980). Orienting of attention. *The Quarterly Journal of Experimental Psychology*, *32*(1), 3–25. https://doi.org/10.1080/00335558008248231

Prinzmetal, W., Presti, D. E., & Posner, M. I. (1986). Does attention affect visual feature integration ? *Journal of Experimental Psychology: Human Perception and Performance*, *12*(3), 361–369. https://doi.org/10.1037/0096-1523.12.3.361

Rastle, K., & Coltheart, M. (1999). Serial and strategic effects in reading aloud. *Journal of*

Experimental Psychology: Human Perception and Performance, *25*(2), 482–503. https://doi.org/10.1037/0096-1523.25.2.482

Roach, N. W., & Hogben, J. H. (2008). Spatial cueing deficits in dyslexia reflect generalised difficulties with attentional selection. *Vision Research*, *48*(2), 193–207. https://doi.org/10.1016/j.visres.2007.11.001

Scaltritti, M., & Balota, D. A. (2013). Are all letters really processed equally and in parallel? Further evidence of a robust first letter advantage. *Acta Psychologica*, *144*(2), 397–410. https://doi.org/10.1016/j.actpsy.2013.07.018

Treiman, R. (2018). What research tells us about reading instruction. *Psychological Science in the Public Interest*, *19*(1), 1–4. https://doi.org/10.1177/1529100618772272

Tydgat, I., & Grainger, J. (2009). Serial position effects in the identification of letters, digits, and symbols. *Journal of Experimental Psychology: Human Perception and Performance*, *35*(2), 480–498. https://doi.org/10.1037/a0013027

Valdoi, S., Bosse, M.-L., Ans, B., Carbonnel, S., Zorman, M., David, D., & Pellant, J. (2003). Phonological and visual processing deficits can dissociate in developmental dyslexia: Evidence from two case studies. *Reading and Writing*, *16*(6), 541–572. https://doi.org/10.1023/A:1025501406971

Valdois, S., Bosse, M. L., & Tainturier, M. J. (2004). The cognitive deficits responsible for developmental dyslexia: Review of evidence for a selective visual attentional disorder. *Dyslexia*, *10*(4), 339–363. https://doi.org/10.1002/dys.284

Valdois, S., Lassus-Sangosse, D., & Lobier, M. (2012). Impaired letter-string processing in developmental dyslexia: What visual-to-phonology code mapping disorder? *Dyslexia*, *18*(2), 77–93. https://doi.org/10.1002/dys.1437

Valdois, S., Roulin, J., & Bosse, M. L. (2019). Visual attention modulates reading acquisition. *Vision Research*, *165*, 152–161. https://doi.org/10.1016/j.visres.2019.10.011

van den Boer, M., & de Jong, P. F. (2018). Stability of visual attention span performance and its relation with reading over time. *Scientific Studies of Reading*, *22*(5), 434–441. https://doi.org/10.1080/10888438.2018.1472266

Vidyasagar, T. R., & Pammer, K. (2010). Dyslexia: a deficit in visuo-spatial attention, not in phonological processing. *Trends in Cognitive Sciences*, *14*(2), 57–63. https://doi.org/10.1016/j.tics.2009.12.003

Weekes, B. S. (1997). Differential effects of number of letters on word and nonword naming latency. *The Quarterly Journal of Experimental Psychology*, *50*(2), 439–456. https://doi.org/10.1080/713755710

Ziegler, J. C., Pech-Georgel, C., Dufau, S., & Grainger, J. (2010). Rapid processing of letters, digits and symbols: What purely visual-attentional deficit in developmental dyslexia? *Developmental Science*, *13*(4), 8–14. https://doi.org/10.1111/j.1467-7687.2010.00983.x

Appendix

Table of words used in reading task

Filler Words	Nonwords			Words		
village	werb	waughs	wergand	blown	peel	charade
slow	arth	anched	angeath	pleat	peach	casket
thoughtless	bipe	biffle	bruntle	spook	reap	prudence
curvy	loat	hoilst	lactond	cough	silk	precinct
crag	klow	clotch	clivest	crow	shelf	oblique
sidelly	doke	drouch	durvact	wove	soar	bourbon
dingert	farp	flotch	fleruch	dough	starch	bearish
pool	gink	glaque	gopless	hearth	steer	salient
punting	heem	heanch	herpame	mould	tempt	sparrow
final	nant	nearch	nistean	pear	wipe	facade
	vilt	veepes	vernand	pint	beech	pumpkin
	lse	ilched	idburge	plaid	bribe	childhood
	noor	nootch	nointed	rouse	brisk	import
	masp	moined	mefless	sew	corpse	discharge
	kine	cranced	klutsam	shove	deem	surplus
	denk	droast	dormand	soot	gloom	thunder
	slig	strink	saigack	sown	fern	witness
	kest	koorph	kedeith	steak	spoil	rainbow
	roog	roitch	ragroke	trough	wail	sunlight
	jile	joives	jollurd	wool	herb	fitness
	wames	wibent	weshness	bead	parent	bedroom
	ampth	abloit	ancloked	brood	chamber	offset
	blace	basple	bestrink	broth	engage	pointless
	loast	lovike	loincing	comb	danger	mittens
	quast	combal	congeare	dome	subtle	snuggle
	doils	daffle	dractare	glove	thorough	slacker
	fause	focate	fraulted	foes	warrant	obstruct
	gatch	gammil	gembrete	squat	regime	duster
	hakes	hoolab	haintule	wart	symbol	mainstay
	noost	nevime	nanchube	hull	frontier	shocker
	voike	vallem	vouseful	barge	squabble	faintest
	ilfed	idvort	insteact	perch	blaring	glimmer
	nelch	nazzle	niscloit	spice	congruent	ostrich
	maint	mejove	moactuse	carve	mishap	thistle
	cloin	kemble	kiscleaf	croak	derail	mouthful
	doint	deboke	derprise	wreck	pheasant	fancier
	scalk	sousle	strindle	dire	thermos	campground
	keent	klorak	kidraint	hoard	mutate	beaming
	reave	roshep	raulined	mince	forbade	groaning
	jeave	joffle	jeafforn	perk	torrent	sparkle