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Word Superiority Effects in Dyslexics

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WORD SUPERIORITY EFFECT IN DYSLEXICS

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By

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Abstract

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Word Superiority Effect in Dyslexics.

Distorting the word superiority effect with intraword spacing was used to investigate the processing difference in single-word reading for dyslexics and controls. Perfetti's Reading model suggests that dyslexics, who have a phonological deficit, would have reduced processing capacity with intraword spacing. Results from a Covid-modified experimental protocol generally did not support the hypothesis. There was poor differentiation between groups in the word capacity coefficient. Response time by itself was also not informative. However, dyslexics had reduced accuracy in distractor identification across intraword spacings due to the lack of retention in phonological working memory or attention in central executive deficit (Alt, Fox, Levy, et al., 2022; Gray, Green, Alt, et al., 2017) as matching targets was not an issue, only confirmation of an update was problematic. In target identification, early responses and later responses were predictive of WIAT III Pseudoword (phonetic processing) and WAIS IV Symbol Search (visuospatial matching task). These preliminary results motivate further research regarding word processing differences in dyslexic and controls.

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Introduction

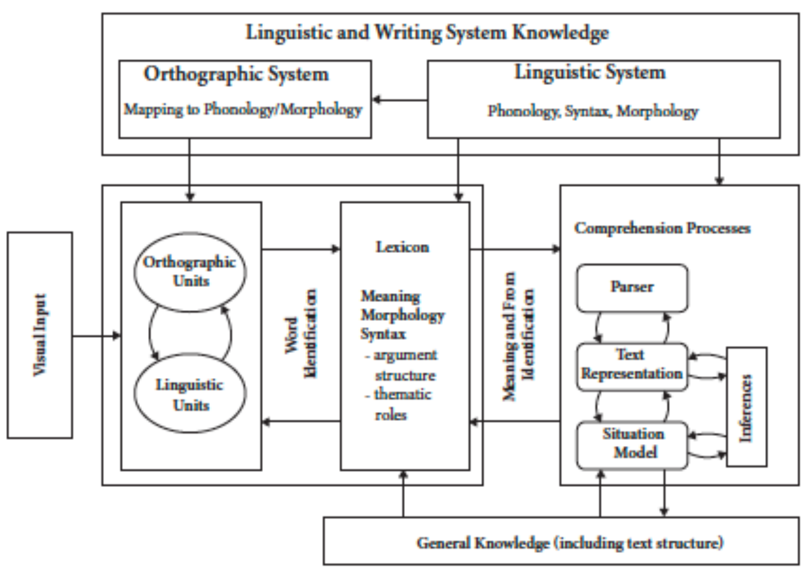
The goal of this research is to contribute to identifying the core processing differences between adults with and without dyslexia when processing single familiar words. Building on Houpt (2015 & in press.), intraword spacing is manipulated in order to disrupt Word Superiority Effect (WSE). Capacity Coefficient and the Assessment Function from System Factorial Technology are theory-based metrics that are used alongside of Bayesian Hierarchical Modeling to examine the group, condition, and individual-level effects of manipulating first and second-order configural properties. First, this paper reviews two general models of typical reading behavior, Perfetti (1999) and Coltheart (2000), and how the Word Superiority Effect can be used to examine how parallel processing of individual letters is different from the perception of a word as a single configural unit. Then, it explains the proposed dyslexic reading model (the neurological perspective on both typical reading and dyslexic reading, drawing on a known distinction between phonetic and logographic languages, that was used to create the dyslexic-specific reading model can be found in Appendix A and B). Finally, the capacity coefficient and the assessment function are briefly explained as a measure of word processing efficacy.

General Model of Reading Behavior

According to the Perfetti model (Figure 1), word identification is the defining capability of reading as opposed to more general language comprehension. In phonetic languages word identification maps visual input into units determined by both orthography (word appearance) and phonology (word sound). The model separates word identification from knowledge-based comprehension processes. According to Perfetti's Lexical Quality Hypothesis, high lexical quality (phonemic and orthographic knowledge) and stability (consistent and correct application of orthography) enable comprehension in verbal working memory. Phonological processing therefore appears to guide the development of automatic word decoding based on orthography and comprehension is built from these phonetic representations of words and their parser within verbal working memory. Although, it is the basic visual unit and word identification differences in the dyslexic population that is examined in this research, it is important to highlight that the standard behavioral measures of reading skill depend on comprehension, and therefore risk contamination due to variability in general knowledge, exposure, and intelligence. This contamination as plagued attempts to use standard psychometric tests to diagnosis dyslexics for

Figure 1

Stafura & Perfetti (2017) Reading System Framework



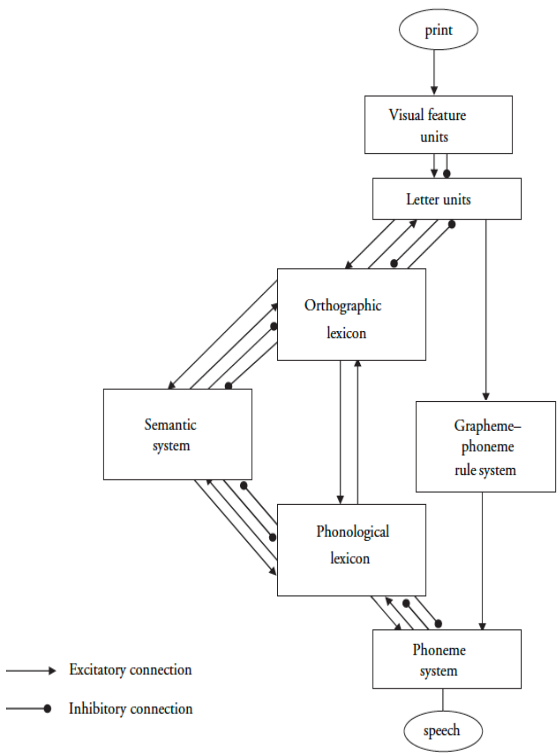
Visual processing, word identification, to comprehension process. Retrieved from Stafura, Joe & Perfetti, Charles. (2017). Integrating word processing with text comprehension: Theoretical frameworks and empirical examples. 10.1075/swll.15.02sta.

over thirty years.

According to Perfetti, low-skilled readers have a deficiency in lexical quality, which is built by serial phonological processing of letters, to the phonetic representation of the word called word identification, followed by semantic identification of the word in the lexicon.

Figure 2

Coltheart (2000) Dual-Route Reading Model



Note. Visual units are processed via the orthographic lexicon or grapheme-phoneme routes for semantic retrieval and speech.

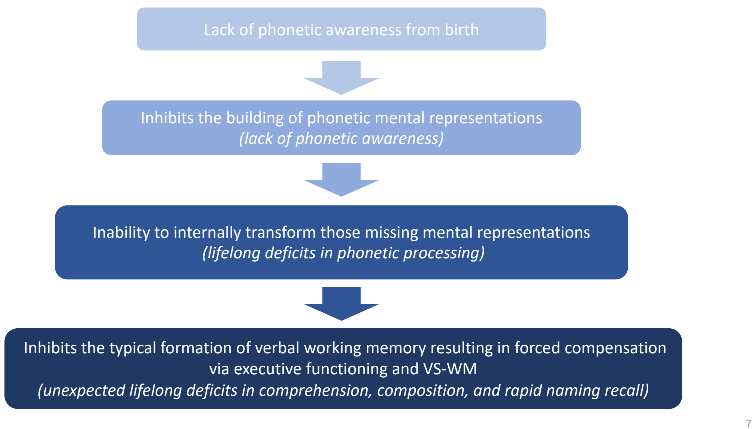
Retrieved from Coltheart, M., Rastle, K., Perry, C., Langdon, R., & Ziegler, J. (2001). DRC: a dual route cascaded model of visual word recognition and reading aloud. Psychological review, 108(1), 204–256. https://doi.org/10.1037/0033-295x.108.1.204

An alternative model is Coltheart's (2001) Dual-Route Theory which can use visual letter units to phonology, phonological word identification, to semantics, *or* visual letter units to orthographic word identification to semantics. Coltheart built the Dual Model from the works of Saussure (1922), Foster & Chambers (1973), and Baron & Strawson (1976; 1977). Both of the routes function in a race model. i.e. they can accumulate evidence in parallel and interact coactively (information in one route facilitate increased certainty in the other route). When a route has achieved certainty, with both excitatory and inhibitory influences, word perception is achieved. There is a lexical and non-lexical route that is dependent on the clarity of letter-level orthography, exposure, and reading silently versus out loud (Coltheart, Rastle, Perry, et al., 2001, p. 30; Figure 2).

The adaptation of the Perfetti model for dyslexics used in this research goes a step further than the Dual Route Model (Coltheart et al., 2001), by removing the individual letter unit. As phonemes are not intrinsically relevant to a population with an unaccommodated phonetic processing deficit, the lowest meaningful unit of recognition used to identify words is the visual word form, sometimes referred to as word envelope, word shape, holistic word shape, or logogram. The word itself is a single unit paired with a lexicon (meaning), which is the acquisitional anchor point that allows for the lowest level of parsing, and then to a holistic phonetic word profile, which also cannot be parsed. However, morphemes have consistent semantic units with consistent corresponding phonetic word profiles. The lowest unit of recognition must have a semantic token. Without a semantic token, the phonetic profiles are just random noise that do not have any face value or apparent consistency for the dyslexic. Logograms or morphemes cannot be broken down into single-character units in visual form (letters) or phonetic form (phonemes) because they have no meaning or mental representation, for the unaccommodated dyslexic. If the dyslexic receives specific and overt training in grapheme-to-phoneme correspondence, especially in languages with clear orthography, dyslexics can learn rote mechanisms to decode words phonetically. This intervention must be taught prior to the maturation of phonetics (accents) and the earlier it is learned, the more likely it is that the lifelong verbal working memory deficit will be reduced. This model assumes the developmental model in Figure 3. This developmental model proposes that the verbal working memory deficit in dyslexia is due to the lack of discrimination of phonetic information from birth. Without the ability to discriminate speech, dyslexic infants use vision and visual-spatial working memory to understand the world around them. Receptive speech delays are a reasonable heuristic of the verbal working memory-building delays. Typically in dyslexics, these are followed by the more apparent articulatory speech delays, which support the verbal working memory delays as words are not the preferred modality of thought or communication. By the time executive functioning is used to teach dyslexics speech via interventions, the neurological changes for phonetic processing that reflect the verbal working memory deficit along with the phonetic deficit are set (Flege, 1988). This is why speech intervention with dyslexics is less effective and works solely through motor repetition, e.g. dyslexics cannot hear the differences in the pronunciations. Dyslexics have an issue with color-to-word correspondence because there is no meaning in color words, so they must learn a key object to decode color, e.g. my fire truck is red. Just as dyslexics cannot learn phonemes until overt phonetic to grapheme training is used, "f " is the first sound in "fire." The sound itself cannot be recalled unless it is paired with meaning via executive functioning. Remembering "f" is the first sound in "fire", so "f" has the sound "f" has far less meaning and is far more complicated than the visual word form "fire" has the sound "fire." This is the reason that the phonetic and spelling deficit does not impact word recognition and why comprehension deficits do not correspond to the phonetic and spelling deficits. This model proposes that dyslexics without intensive intervention word recognition is logographic and comprehension deficits are due to the preference to use the overdeveloped visual working memory over the underdeveloped verbal working memory when reading.

Figure 3

Proposed Dyslexia Developmental Cognition Model



Note. Dyslexia developmental cognitive model is based on the current body of neurological and psychometric evidence. The lack of phonetic awareness from birth inhibits the construction of phonetic mental representations. This in turn causes the inability to internally transform those missing mental representations, leading to a lifelong deficit in phonetic processing including blending/decoding words. Finally, the inability to internally transform those missing representations, interferes with the typical formation of verbal working memory. Dyslexics, who do not receive proper interventions, learn to compensate for the deficient verbal working memory with executive functioning and VS-WM; nevertheless, there are the long-term achievement and intelligence independent deficits in reading comprehension, composition, fluency, and rapid naming recall.

Word Superiority Effects and Word Processing Research

The word superiority effect (WSE) is a well-established phenomenon in which individual letters are more readily detected when they are embedded in legal words (Cattell, 1885; Reichert, 1969; Wheeler, 1970). The lesser-known pseudoword superiority effect is that pseudowords, which are pronounceable non-words that have legal orthography, are identified more readily than nonlegal, unpronounceable letter strings (Grainger, Bouttevin, Truc, et al., 2003; McClelland, 1976). The general explanation for the word-superiority effect postulates greater automaticity in the retrieval of phonetic and semantic information due to visual expertise of frequently viewed words/morphemes/bigrams.

Previous research on dyslexics and WSE report mean RT and accuracy rates rather than theory-driven analyses as found in Houpt et al. (2015). Using specialized distractors (pseudoword, nonword, and Japanese characters), Houpt's theory-based capacity coefficient was calculated for each subject. All scores were run through a functional principal components analysis which discriminated three groups that correspond to standardized cognitive composite score for verbal IQ, achievement subtest for grapheme-phoneme conversion (Word Attack subtest), and Lefty (2000) reading history survey. The dyslexics were part of two groups, one with low verbal working memory and phonetic scores and one that performed similarly to controls. In this research, we are running additional cognitive and achievement subtests and modeling individual subtest scores to confirm the typical pattern of deficits in dyslexics and to explain variations in performance with selected constructs represented by the cognitive and achievement subtests.

Traditional response time and accuracy measures

Mean response time comparisons have been the standard practice for mental processing comparisons for over 150 years (Roelofs, 2018). The majority of silent single-word perception research for the dyslexic population used aggregated measures as their dependent variables rather than preserving the ratio scale in RT in data. These studies also avoided the established findings about the processing architecture and distribution characteristics of their measures, e.g. words are processed in parallel (Dehaene et al, 2005), skewed RT distributions (Baayen et al, 2010; Ratcliff, 1993). Traditional analyses did nonetheless bring forward important findings for word and letter perception.

In non-dyslexic populations, Cohen et al.(2008) found reduced anterior VWFA activation and increased posterior activation as word stimuli degradation (intraword spacing) increased. Cohen et al. assumed that parallel processing by the left occipitotemporal cortex gives way to serial processing of the distorted word stimuli via the dorsal parietal cortex. Mean RT comparisons with ANOVAs or t-tests are the norm for behavioral, cognitive, educational, and neurological psychologists who have embraced this measure with phenomenal success. In a neurotypical population, Vinckier, Qiao, Pallier, et al. (2011) found that accuracy and RT were degraded with three and four-times intraword spacing, and an effect of word length largely contributed to the accuracy of four and eight-character words and the RT of the six and eight character words. In dyslexic populations, Grainger et al. (2003) found that dyslexic children performed similarly to reading-age matched controls and chronological-age matched controls in accuracy in a visual word match task (Reicher-Wheeler task) despite poor performance in pseudoword articulation. Zeigler et al. (2008) found dyslexics children were not significantly different from controls for RT for WSE.

Replication with contemporary analysis methods provides additional insight. Response time data typically constitute a skewed distribution (Baayen et al, 2010; Ratcliff, 1993), and are therefore not a good fit for conventional null hypothesis testing. While taking the log of the dependent variable distribution is commonly found in psychological research, doing so distorts the distributional relationships between responses. This distortion is it is not necessary when Bayesian methods are used. Given the increase of accessibility and simplicity of Bayesian analyses, reducing subject or group level data to means (or otherwise transforming the data) causes unnecessary loss of information that can distort results by increased chance of inferential errors, distorting effect sizes, or altering relationships in multivariate datasets that negatively impact the validity of the results. When combined with violations of homogeneity, null hypothesis tests give a false impression that between and within groups' performances are more uniform than what is reflected in the subject-level data as it changes the relationships in the data

(Feng, Wang, Lu, et al., 2014; Pearson & Neyman, 1933). Handling response time data within the Bayesian framework, assuming it is completed correctly (Singmann, Kellen, Coc, et al., 2022), has greater content and face validity. Further, the word capacity and the assessment functions within System Factorial Technology (SFT) provides an analysis technique that accounts for the known processing architecture and the processing/stopping rules used when integrating multiple sources of information. This tailored analysis provides better control of general response latencies, individual subjects' variations not associated with the experimental manipulations, and maintains a ratio scale.

Phonetic and logographic languages

Phonetic written language is less complex than pictographic and logographic language. The difficulty of learning and using pictographic and logographic languages has led to the extinction of pictographic and the non-primary use of all remaining logographic languages (Gelb, 1952; Zhu, 1987). From an ecological viewpoint, there are greater restrictions in the construction (lingual dexterity) and identification (auditory perception) of exclusively spoken language than in the construction (finger dexterity) and identification (visual perception) of written language. Typically, phonetic written language corresponds closely with the spoken language (one to one grapheme-to-phoneme correspondence) (Sproat & Gutkin, 2021). Logographic written languages traditionally do not primarily rely on grapheme to phoneme correspondence, but rather orthography to semantics. The only modern logographic language, Kanji, has tonal and phonetic correspondence (syllabic and phoneme) for the phonetic components and inconsistent correspondence of phonetic/tonal to semantics for the logographic components forcing logogram to semantic processing (Cao, Lee, Shu, et al, 2010; Ho & Bryant, 1997; Ho & Bryant, 1999; Ho, Chung, Lee, Tsang, 2007). Due to the inconstancies, there is increased visual symbol complexity in order to differentiate each syllable or word (Hua &

Perfetti, 2003; Ho & Bryant, 1997; Ho & Bryant, 1999; Sproat & Gutkin, 2021). Logographic reading is a plausible compensation for the literate dyslexic without phonetic training; without the ability to identify, blend, or decompose phonemes, word recognition is paring of a visual symbol to a meaning and/or to a phonetic pattern.

Phonetic languages and associated neurological processing

In phonetic languages, VWFA and posterior superior temporal sulcus activation provides automatic phonological -orthographic conversion, followed by left posterior middle temporal gyrus staging for consolidation, and subsequent semantic processing by the anterior middle temporal gyrus (MTG) with functional connectivity with the default mode network and inferior prefrontal cortex yielding comprehension and inference (Carreiras, 2009; Chen, 2019; Davey, 2016; Nakamura, Dehanae, Jobert, et al., 2005; Perfetti, 1999; Richlan, Kronbichler, & Wimmer, 2009; Barbeau, Descoteaux, & Petrides, 2020 Snowling, 2005). According to Dehaene's Neuronal Migration Hypothesis, the associative pairing of letters/words and phonemes/spoken language (left temporal cortex) causes a neuronal migration where the left FFA tunes to the specific categorical stimuli. This stimulus is identified as a component of language and through associative learning is functionally connected to the prior auditory and spoken language networks. As acquisition occurs, the high lexical quality and stability can be established as relatively high activation (high lexical quality) and specificity (stability) in the left FFA, now the visual word form area, (Dehanae & Cohen, 2011; Manzavio, De Luca, Trezzi, et al., 2012). The articulus facsucus/inferior longitudinal facsicatis volume of white matter pathways between the VWFA and the left temporal lobe is predictive of behavioral reading measures. The arcuate facsucus/inferior longitudinal facsicatis between the VWFA and the posterior superior temporal sulcus processes the phonological to orthographic mapping to prepare for written word semantic retrieval (Chen, 2019; Hannagan, Agrawal, Cohen, et al., 2021) which a white matter tract known to be reduced in dyslexics from infancy (Langer, Peysakhovich, Zuh, et al., 2019) and behaviorally targeted in this research. Finally, the left superior middle temporal gyrus facilitates the processing of semantic matching by the remaining anterior MTG, posterior MTG, and medial MTG (Xu, Lyu, Li, et al., 2019).

As the pairing of visual and phonetic input stabilizes with repeated exposure, the process becomes automatic (Chen et al., 2019; Jitsuishi, Hirono, Yamamoto, et al., 2020) and it requires less attentional control (de Schotten, 2014; Vidyasagar, 2019). Perrone-Bertolotti's (2014) grapho-phonemic conversion emphasizes that the visual stimulus to phonetic association is top-down as well as bottom up. While the bottom-up influence of the VWFA is clear, the top-down influence drives more complex differentiation and identification of written language. The functional connectivity of the fronto-parietal attention network nodes (top-down influence) can predict behavioral scores in reading, though reading scores cannot predict scores of behavioral attentional measures (Chen, 2019). Sharoh, van Mourik, Bains, Segaert, Weber, Hagoort, and Norris (2019) found that top-down modulation from the left middle temporal gyrus assists in the identification if orthographic compliance is unclear as well as contributes to controlled semantic retrieval (Davey, Thompson, Hallam, et al., 2016). Native language orthographic clarity also contributes to neurological compensatory mechanisms (Martin, Kronbichler, & Richlan, 2016), acquisition of reading skills (Landerl, Wimmer, & Frith, 1997), and performance on diagnostic tests (phonetic awareness, rapid naming, and short-term working memory) (Landerl, Ramus, Moll, et al. 2012). Activation of the left inferior frontal gyrus and ventral occipitotemporal cortex was found in non-dyslexic English language subjects is theorized to represent the shared orthographies reading and spelling tasks (Purcell, Jiang, & Eden, 2017), which are areas associated with under activation in dyslexics (Finn, et al., 2014; Richlan, et al., 2009).

Logographic languages and associated neurological processing

Logographic reading does not follow Perfetti's Reading Process Model (Perfetti, et al, 2005; Perfetti, 2006). Phonology is a post-lexical task in logographic languages (Dylman & Kikutani, 2018). Logographic reading takes visual input as morphemes or morphosyllibic units; each morpheme/morphosyllibic unit within the logogram has a semantic meaning to use alone or build upon, similar to deriving meaning from uncommon and complex Latin and Greek words (Chen & Kao, 2002; Dylman, 2018; Cole, 2007; Wong, Tong, Lui, et al., 2021). Logographic reading depends on the one-to-one correspondence of the morpheme and the semantics in order to be derived, though there are many contrary instances (Sproat & Gutkin, 2021). The reader can deduce the proper semantic interpretation until automaticity in reading is obtained. In logographic languages, there will be a temporal delay in retrieving phonetic representations (speaking) compared to phonetic language readers; thus, phonetic retrieval is identified *after* the semantic meaning, delaying verbalization of a single word (Dyllman, 2018). Logographic comprehension employs a situation model within central executive working memory using feature salience and spatial relationships rather than linear ordering of phonemes and grammar (Chen & Kao, 2002; Wong, et al., 2021; Yang, Zhang, & Meng, 2018). Studies of Chinese logographic reading (Kanji) have shown bilateral activation of the OTC (VWFA/FFA) while reading logograms compared to greater left lateral activation for phonetic words, along with increased intraparietal functional connectivity, and increased connectivity of the left middle temporal gyrus (anterior and mid as semantic processing and posterior as language processing), and reduced white matter pathways between the left arcuate fasciculus and inferior fronto-occipital fasciculus (Dong, Nakagawa, Okada, et al., 2005; Nakagawa et al, 2005; Su, Zhao, de Schotten, et al., 2018; Xu, 2019; Yamaguchi et al., 2002; Zhang et al., 2013; Zhang et al., 2014). The increased activation of the right temporal lobe and right to mid FFA are believed to be associated with visual spatial to orthographic processing (Smith, Jonides, Koeppe, et al., 1995). Logographic written language has greater activations in the ventral pathway while (Tau, Laird, & Li, 2005) phonetic had greater activation in the dorsal pathway (Kim, Kim, Kang, et al., 2017) which provides a context for the heavily visuo-spatial sensitive languages to be processed differently than the heavily temporally sensitive auditory processing of phonetic languages.

Dyslexic reading network and reading process for phonetic languages similar to logographic languages

Genetic and neurophysiological research describe dyslexia in terms of atypical neuronal positioning and axon growth during midgestational development (Galaburda, Sherman, Rosen, et al., 1985; Galaburda, LoTurco, & Ramus, 2004; Mascheretti, et al., 2017). The resulting ectopias and dysplasia prevent typical pathway connectivity (Keri, 2014) and asynchronous activations in higher-order processing integration (Hairston, Burdette, Flowers, et al., 2005). Neurological differences can be identified in infancy (Guttorm, Lappanen, Hamalainen, et al., 2010; Langer, Peysakhovich, Zuk, et al., 2017; Mascheretti et al., 2017); These structural and connectivity differences result in weak phonemic awareness and deficient orthographic resources despite later training in childhood/adulthood (Martin et al., 2016).

The ability to differentiate rapid auditory stimuli and pull apart the phonemic information from birth is imperative for development of the language areas along the articulus facsucus/inferior longitudinal facsicatis (Del Tufo, Earle, & Cutting, 2019; Sket, Overfeld, Styner, et al., 2019). Langer, Peysakhovich, Zuh, et al. (2017) found significant reductions in white matter tracts in the articulus facsucus/inferior longitudinal facsicatis in 18-month-olds with a family history of dyslexia. The reduced volume of left planum temporale (PT) is associated with reduced temporal precision in auditory processing that prevents phoneme discrimination and blending (Ocklenburg, Frederich, Fraenz, et al., 2018). Speech delays and reduced vocabularies are also common in children with a family history of dyslexia (Chen, Wijnen, Koster, et al., 2017; Koster, Been, Krikhaar, et al., 2005). There are well-documented right lateralized activations in FFA, planum temporale (left PT is smaller than typical and right PT is larger than neurotypical), and increased right posterior parietal activations (Bloom, Garcia-Barrera, Miller, et al., 2013; Eicher, Montgomery, Akshoomoff, et al., 2015; Finn, Shen, Holahan, et al., 2014; Richlan, et al., 2009; van der Mark et al., 2011) suspected to compensate for the under activations of the left OTC in dyslexics (Finn, et al., 2014; Richlan, et al., 2009; Ziegler, 2006). However, the right planum temporale is cellularly unequipped for high specification in temporal frequency-sensitive discrimination (Ocklenburg, et al., 2018; Virtala, 2020). This is combined with the under-activation of the left inferior frontal gyrus, left temporal region, and the left dorsal inferior parietal to ventral occipitotemporal regions (Richlan et al., 2009). Additionally, dyslexics cannot fully compensate for the loss in typical automaticity in grapho-phonemic conversion despite being supported by left inferior parietal lobule (motor-articulatory area) (Pekkola et al., 2005) and attentional networks (increased activation of the dorsal anterior cingulate cortex and increased interconnectivity of posterior cingulate cortex to the dorsal anterior cingulate cortex and medial prefrontal cortex) (Aden, 2020; Finn, 2014; Richlan, et al., 2019). Zaric, Timmers, Gerretsen, et al. (2018) found increased bilateral anterior thalamic white matter tracts connectivity in literate dyslexic children that correlated with behavioral reading measures suggesting that the increased effort to learn to read/improve reading skill (attentional and working memory) were responsible. This can be interpreted as without the ability to discriminate or blend phonetic information, phonetic written language is missing its primary affordance, i.e. the phonetic correspondence with the spoken language, and therefore requires additional attention and working memory resources.

Literate dyslexics have a modified “reading circuit” (Finn et al., 2014; Garbreili, 2009; Richlan et al., 2009). When presented with word/sentence visual stimuli, dyslexics have atypical bilateral diffusion of FFA/VWFA activation (Finn et al., 2014; Kubuto et al., 2019; Hannagan, Agrawal, Cohen, et al., 2021) because the symbols are not reliability associated with phonemes (Blomert, 2011). Children who were reported to be dyslexic by parents (Kubuto et al., 2019) had bilateral activation of the FFA for words/letters and did not show typical specificity in the left FFA/VWFA for words/letters over objects (Finn, et al., 2014; Kubuto, et al., 2019). In basic letter reading, dyslexic children do not suppress the symmetrical equivalence of letters (e.g., “b” vs “d”) and perform similarly for arrays of dots and letters (Lauchmann & Ven Leeuwen, 2007) further supporting the concept that letters are not differentiated from simple shapes, i.e. letters are not special (connected to the phonetic language network) in dyslexic children. Automaticity in grapheme-phoneme conversion remains lacking in dyslexic children despite intensive graph-phonetic conversion training (Ellis, 1985; Torgesen, Wagner, & Rashotte, 1994) and in literate dyslexic adults in an orthographically clear language (Blau, van Atteveldt, Ekkebus, et al., 2009). This lack of automaticity in grapheme-phonetic conversion is the cause for the dyslexics’ deviation in both Perfetti’s Reading Model and Coltheart’s Dual Route Model and indicates dyslexics use effortful, internally directed processing to convert written language to phonetic representations. Elbro and Arnbak (1996) suggest dyslexics used morpheme identification for word recognition rather than a phonetic decoding strategy, and morphologic system identification could accommodate for the phonetic deficit (Casalis, Cole, & Sopo, 2004; Deacon, Tong, & Mimeau, 2019; Leikin & Hagit, 2006). While useful, the morphological system of reading cannot fully replace phonetic decoding because the inherent structures of phonetic languages do not always follow morphology. Also, it is memorization intensive; morphological identification requires rote memorization of both symbol groupings and phonetic groupings instead of an algorithm to decode any word. Lastly, morpheme groupings must be blended in compound words ("chunking"), and while it is easier to blend the morphemes than a string of phonemes and semantic information is helpful, whole word phonetic retrieval can still be impaired (even after semantic identification) (Katz, 1986).

There are many other neurological deviations beyond the phonetic defect correlates, including white and gray matter volumes, atypical activation, and pathway patterns, that are less consistent within the dyslexic population (Mascheretti, et al.,2017; Martin, et al., 2016) and are assumed to be related to the structures and consistencies within the language, exposure, and compensation techniques. The ability of dyslexics to learn to read despite the physical structural abnormalities on the left OTC and associated white matter pathways shows 1) the plasticity in the visual and language centers of the brain, 2) modifications in processing that yield the same outcomes when typical affordances are removed, 3) reading instruction can be modified to teach all students, including the approximately 10% of the students that are dyslexics, with improvements in orthographic clarity and modified methods based on processing and neurological evidence, 4) lack of phonological processing from birth and related receptive and expressive language delays result in a deficit due to lack of typical use, in verbal working memory, 5) increased used of visual-spatial working memory to compensate for the verbal working memory deficit, 6) the instruction of artificial languages (programming languages) should mirror these new innovations of reading instruction (specific meaning based rather than learning by inference). Understanding the implications of these statements is critical to creating a universal dyslexia model and a contamination free diagnostic tool, as well as a better understanding of a universal and language specific reading models.

Word Superiority Effect and Dyslexia

Configural processing generically refers to the processing of perceptual stimuli's components as a whole rather than their individual pieces (Gestalt holistic processing). The increased affordances for processing that are gained by the combination of attention, expertise, and/or neurological predeterminism, make configural stimuli special when compared to other stimuli. Faces are the traditional stimuli in configural processing, e.g. humans are better at identifying familiar faces as a whole, than as pieces (Tanaka & Farah, 1993), and altering spacing reduces accuracy in the identification of familiar faces (Tanaka & Sengco, 1997). Configural research on word perception is largely associated with manipulations using the Word Superiority Effect (Farah, Wilson, Drain, & Tanaka, 1998). In configural research, the first-order effects correspond to features in a specific configuration (eyes or letters) and second-order effects are variations in spacing/positioning of the features (distance between features or intraword spacing) (Diamond & Carey, 1986; McKone, 2008; Maurer, le Grand, & Mondloch, 2002; Schwaninger, Lobmaier, Collishaw, 2002; Sergent, 1984, 1986). The addition of intraword spacing can be described as correcting for crowding as the dyslexia font research suggests (Rello & Baeza-Yates, 2013), or disrupting visual holistic processing (visual expertise of word reading due to exposure – assuming typical exposure is normally spaced).

The lowest level of reading processing affected by dyslexia that can be supported by neurological, behavioral, and psycholinguistic research is Perfetti's (2001) Orthographic Mapping to Phonology/Perrone-Bertolotti (2014) grapho-phonological conversion. The automatic grapho-phonemic conversion produces the word superiority effect, i.e. processing words at supercapacity, as children (7 year old) learn to read (Chase & Tallal, 1990). Adult literate dyslexics also have a word superiority effect due to their respective compensation strategy, though literate dyslexic children (average age 11.5) do not (Grainger et al., 2004). Consistent with the bigram coding hypothesis (Vinckier, Qiao, Pallier, et al., 2011) and the local combination detector (LCD) model (Dehaene, Cohen, Sigman, & Vinckier, 2005), distorting visual word stimuli will interrupt the typical automatic visual processing that yields the word superiority effect, and force the use of a compensatory process of phonetic blending or letter/digit span task (repetition of seral string of letters/numbers) both of which are known to be deficient in dyslexics. The effect of distortion should be robust in dyslexics, independent of the past intervention or compensatory strategy, while having a minimal effect in the controls.

System Factorial Technology's Capacity and Assessment Functions

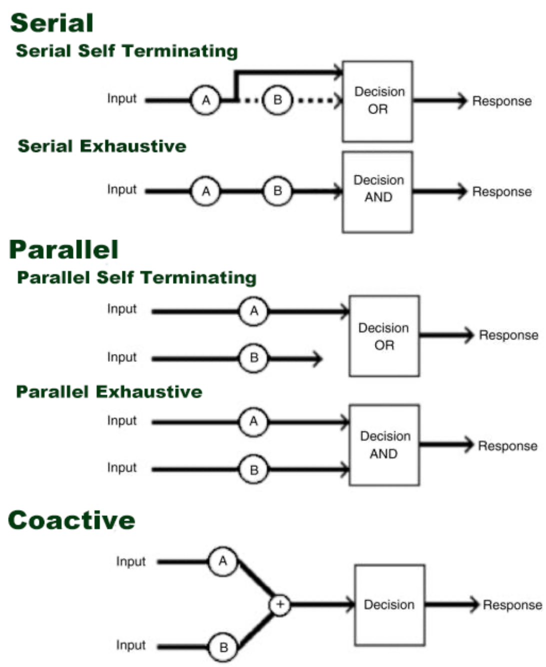
System Factorial Technology (SFT) is a family of theory-based statistical tools used to examine cognitive workload. SFT improves upon traditional response time and accuracy measures (Sternberg, 1966) by providing a more detailed architecture and stopping rules for the accumulation of information that can account for stimulus-specific perceptual and neurological restrictions/affordances as well as compare quantity or salience of the objects being processed without redundancy effects. SFT's capacity and assessment functions (Houpt & Townsend, 2012, Townsend & Altieri, 2012) are theory driven measures that provide direct comparisons of processing efficiency. Both are nonparametric analyses that account for accuracy (categorically or as a rate) while comparing the probability of response time distributions (probability of correct response has not occurred by time t or probability for response by time t (correct or incorrect)). The baseline distribution, or the Unlimited Capacity, Independent, Parallel (UCIP) model, is the combined single-channel distribution, which is compared to the observed performance of multiple channels presented simultaneously. Nonparametric, semiparametric, or frequentist tests can be used to quantify processing efficiency, meaning the extent the subject can process and internally manipulate information, as limited, unlimited, or super capacity (Altieri, 2017; Houpt, 2017).

The capacity coefficient and the assessment function may be grouped into limited, unlimited, or supercapacity based on whether the participant was respectively less efficient, equally efficient, or more efficient than a baseline prediction. In addition to that qualitative evaluation, the measures can be used to quantitatively compare individual subjects or groups. For quantitative comparisons, the capacity coefficient (for correct responses only) may be summarized with a single z-score (Houpt & Townsend, 2012). Alternatively, the variation across functions can be reduced to a limited set of values by utilizing functional principal components analysis (FPCA; Burns, 2013). The assessment function produces a measure of processing efficacy across time (it is not averaged to a single score per person or group like capacity) and therefore produces a more general grouping of limited, unlimited, and supercapacity over time, or even as changing processing groupings over time.

SFT categorizes tasks by properties of information processing for mental operations, specifically architecture and decision rules (Townsend, 1972,1976b; Snodgrass, 1980; Townsend & Ashby, 1983; Townsend & Wenger, 2004; see Figure 4). Architecture is typically described as the different manner in which bits of information accumulate in channels in order to make a determination about a given object or group of objects. Architectures are then broken down into decision or stopping rules, self-terminating, exhaustive, or single target self-terminating. Serial processing, meaning objects can only be processed one at a time, can be self-terminating (the response is given as soon as a channel accumulates enough information) or exhaustive (all channels have accumulated sufficient information before a response can be generated). Parallel processing, meaning multiple objects can be processed simultaneously, can be self-terminating

Figure 4.

System Factorial Technology Architecture and Decision Rules



Adapted from: Johnson, S. A., Blaha, L. M., Houpt, J. W., & Townsend, J. T. (2010). Systems Factorial Technology Provides New Insights on Global-Local Information Processing in Autism Spectrum Disorders. Journal of Mathematical Psychology, 54 (1),

Architecture

Serial: *The processing of the first channels must be complete prior to beginning the processing of the second.*

Parallel: *The channels are processed simultaneously.*

Coactive: *The channels are processed jointly where the channels' information is shared resulting in faster responses than parallel processing.*

Decision Rules

Self-Terminating: *Processing stops as soon as the target is identified.*

Exhaustive: *Processing stops once all channels have completed processing.*

or exhaustive. Both serial and parallel architectures assume that the channels accumulate independently from the others. Coactive does not assume independence accumulation though it is similar to parallel processing where multiple objects are processed at the same time. Coactive processing assumes the information from each channel accumulates in a joint channel allowing information from one object to provide information about the others and exhaustive processing is required. Single target self-terminating is the decision rule that allows for a single channel to be processed while ignoring distractors. Once a task is incorporated into this framework, the appropriate corresponding analyses facilitate the categorization/quantification of capacity as a measure of mental workload efficacy.

Word Capacity Coefficient

The word capacity coefficient (Houpt, Townsend, & Donkin, 2010; Houpt & Townsend, 2012) serves as a measure of workload processing efficiency for accurate single-word processing. The individual letters of a word stimulus are assumed to be processed using a parallel architecture (Houpt, et al., 2010; Estes, 1975; Massaro, 1973) meaning all channels are processed simultaneously (in contrast with serial, one channel at a time, or coactive) whereby increasing the number of channels increases per unit efficiency. For this research exhaustive processing is assumed; meaning, all letters must be processed before the subject can respond, which restricts the conditions used in the word capacity coefficient to targets. Therefore:

$$\text{Eq. 1 } P\{RT_{word} \leq t\} = P\{RT_1 \leq t, RT_2 \leq t, RT_3 \leq t, RT_4 \leq t\}$$

The probability that the subject has processed the word (e.g. “care”) by the time *t* is equal to the probability that the subject has processed each of the letters (e.g. “c,” “a,” “r,” and “e”) by that time. To establish a baseline, we assume that the letters are processed independently and in parallel and therefore, using the multiplication rule, we can convert the intersection of these likelihoods into the product of the individual terms,

$$\text{Eq. 2 } P\{RT_{word} \leq t\} = P\{RTi \leq t\}*P\{RTi \leq t\}*P\{RTi \leq t\}*P\{RTi \leq t\}.$$

The natural logarithm is taken of both sides to convert the likelihoods (cumulative density functions) into a Cumulative Reverse Hazard Function (CRHF) (the Nelson-Aalen estimator is used to convert the single letter responses and the word responses to cumulative reverse hazard functions within the SFT package (Houpt, 2018)). The number of letters in the word condition is used to determine the number of single-letter CRHF (K_i) that are summed for the numerator of the capacity equation. Then the capacity coefficient is produced by their proportion, i.e. the cumulative reverse hazard function for the word condition (K_{word})is used as the denominator and the UCIP model (the summation of the single characters CRHF) is the numerator. The capacity coefficient is then converted to z-scores with the UCIP model (C(t)= 1) as the null hypothesis. If C(t) z-score is two standard deviations less than 1, capacity is classified as limited processing. Or, if C(t) z-score is two standard deviations greater than 1 capacity is classified as super capacity. Otherwise, it remains categorized as unlimited capacity.

$$\text{Eq. 3 } C(t) = [\ \Sigma K_i]\ / K_{word}.$$

(C(t) interpretation: Limited capacity < 1; Unlimited capacity = 1; Supercapacity > 1)

Assessment Function

The assessment function uses the same architecture, stopping rules, and UCIP race model as the baseline capacity. Responses can be categorized as Fast or Slow and Correct or Incorrect. While the assessment function also uses an accuracy rate, if a subject's accuracy rate is very close to 100%, the assessment function and the capacity function will have identical results. The function will produce plots for visual inspection and categorization of the correspondence of the data to the UCIP baseline model (A(t)<1 is limited, A(t)>1 is super capacity). Typically, the accuracy rate needs to be above .9 to meet the basic processing assumptions; exhaustive processing requires each letter must be examined. If the accuracy rate is low, there is no mechanism to confirm exhaustive processing has occurred.

The SFT package for R was used to calculate these functions, as well as functional Principal Component Analysis and z-scores that can be used in modeling (Houpt & Blaha, 2013). Interested parties should refer to the System Factorial Technology book (2017) and SFT R documentation (Houpt, 2013).

The Assessment Function (Townsend and Altieri, 2012) investigates mental processing workload capacity in relation to the UCIP model using similar logic, but unlike the capacity coefficient, it uses both RT and accuracy rate. It combines the accuracy and response time into a single function

$$\text{Eq 4. } \int (P_{AB}T_{ABC} = t' < T_{AB_i})dt' = P(Correct) \cdot P(T <= t \mid Correct).$$

The function represents the probability of a correct response times the probability that the response time is less than time *t* given it was correct. This is then transformed,

$$\text{Eq. 5. } log\ [P_A\ (T<=\ t|Correct)\ \cdot P_A\ (Correct)] + log[P_B\ (T <= t|Correct\ \cdot P_B(Correct)]$$

$$log(P(_{AB}(T<= t|Correct) \cdot P_{AB}(Correct).$$

The log [P(Correct) • P(T <= t | Correct)] is used for each channel of information (single channel or holistic); the summation of the single channels distributions for the needed number of channels (four single characters) is the numerator and the holistic channel (four letter word) distribution is the denominator.

Experiment overview

Response time and accuracy were recorded and expected to be predicted by spacing conditions (second-order manipulation), target versus distractor conditions (first-order manipulation), and the location of the distractor within the word (orthographic processing manipulation). A single character conditions are used to predict the unlimited capacity, independent, and parallel model for the capacity coefficient and assessment functions. Psychometric cognitive and achievement tests were used to explain variations in the assessment function’s principal components, median RT, and accuracy rate. Subject level variability is accounted for by using the subject variable as a random intercept in all repeated measure models. Additionally, a background survey concerning compositional deficits and rates of intervention in the population is included.

Hypotheses

Hypothesis I: Super capacity will be found for all subjects in the normal spaced conditions. Both dyslexics and controls will perform at supercapacity in normal spaced conditions, as reported by Houpt et al., (2015). While dyslexics have varying skills in reading speed and reading comprehension, there are minimal differences in single-word reading RT in dyslexics from controls in literate adults.

Hypothesis 2: Super capacity will be found for controls and dyslexics with high IQ, phonetic, and coding score groupings, and unlimited capacity for all other dyslexics in the fivefold intraword spacing condition. Due to increased ability in working memory capacity and exposure to phonetic compensation techniques, dyslexics within the top 30% of higher functional IQs, phonetic scores, and coding scores will be able to hold supercapacity at the five-fold spacing condition, as well controls (unless in the 30% below standard in functional IQ), phonetic scores, and coding scores. All other dyslexics will operate at unlimited to limited capacity.

Hypothesis 3a: Unlimited capacity will be found in controls and limited capacity for dyslexics at the eightfold spacing condition. At the eightfold intraword spacing condition, all dyslexics will be beyond any compensation strategy. For the eightfold visual stimulus deteriorated beyond the activation of the anterior VOTC (Cohen, 2005). Without this activation, the adaptive phonetic compensation to visual input will not occur and it will become a working memory task in dyslexics. Controls will still be able to determine compliance or deviation. The control's orthographic compliance check will occur at unlimited capacity due to this benefit of neuronal automaticity within the phonetic language circuit. Dyslexics will be forced to use single-character coding that requires recall of temporally specific location of visual stimuli and as dyslexics cannot recall or even differentiate temporally sensitive stimuli, no matter the perceptual input or behavioral output (Tallah, 1984), their processing efficiency will be worse than controls. Hypothesis 3b: In the eightfold condition, there will be strong support for the main effect of group. Specifically for this type of stimuli, due to dyslexics altered reading processes which require logographic to semantic processing to occur before orthography, and known difficulties with consolidation compliance, dyslexics will operate at limited capacity in the eightfold task.

Hypothesis 4a: The mean response time will show strong support for a main effect of group, spacing, and target/distractor. Hypothesis 4b: The mean accuracy rate will show positive support for the full model with a spacing condition, group, and location three-way interaction.

Post Hoc Experimental Analysis Hypotheses/Research Question

Hypothesis 5: There will be strong support for the effect of group, location, and spacing condition for the accurate distractor trials. The effect of location of the distractor and accuracy will be examined to investigate compliance to orthographic presentation rules in dyslexic and further examine the costs of a logographic reading process in phonological language reading. Lastly, to confirm that the experimental task captures greater construct relevant variance than typical diagnostic tools, I will compare the accuracy and reliability with the WIAT and WAIS scores.

Hypothesis 6a: In fivefold conditions, a dyslexic's response time and accuracy rate will predict scores on Wechsler Individual Achievement Test (WIAT) phonetic processing (Pseudoword and Spelling), verbal working memory (Digit Span), and coding (tests sensitive to temporal processing). While there will be slight differences in the capacity categorical identification, there will not be a significant difference in the capacity score within each condition within each group, making the task more resistant to the effects of intelligence and past intervention on the current diagnostic standardized tests. Hypothesis 6b: The Wechsler Adult Intelligence Scale (WAIS) and WIAT discrepancy scores will predict WAIS IQ Scores (where high and low IQ will have reduced discrepancy scores and +/- 1.5SD IQ will show the greatest discrepancy range). The capacity coefficient scores will not significantly explain the variance within or between group WAIS scores (only as in the expected results for stages of skill acquisition); therefore, Hypothesis 6c: The capacity index for dyslexia will not significantly predict WAIS Full IQ Scores for any subject.

Method

Participants

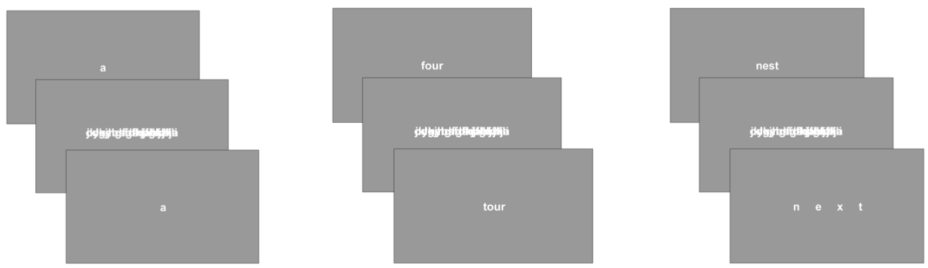
Twenty dyslexic subjects (mean age 23.8) were recruited from five midwestern universities via their disability's services offices, three of which were in post graduate certification/studies (one education masters and two in medical school). The average age of dyslexic or SLD-Reading diagnosis was 10.2; median age 8.5; range age 5 to age 21. Seven out of the twenty did not receive reading or phonetic interventions and twelve out of the twenty did not receive speech services. Twenty controls (mean age 22.0) were undergraduates from one of the five midwestern universities recruited from their undergraduate research pool. Five control subjects with a positive history of reading intervention, speech intervention, or positive family history of dyslexia were excluded (family history of reading issues that were not dyslexia were not excluded). Subjects who did not complete all three spacing conditions or the psychometric tests were excluded. Non-native English speakers were not excluded (two controls and one dyslexic). Dyslexic subjects received $10 per hour and controls received course credit for the two 90-minute sessions. All subjects completed an electronic informed consent. All subjects had normal or corrected to normal vision documented via a self-report survey.

Materials

There were two primary conditions, English single-syllable four-letter words, and a single character. For the word conditions, there are three condition blocks (normal, five times, or eight times spacing) containing 175 trials each. For the single character conditions, there were three versions; one with the location centered and two with varied by possible letter location within the corresponding with the available positions in the five and eight spacing word conditions (referred to as varied position character trials). Subjects were asked to determine if the first presented stimulus matched the second presented stimulus. In target trials, the cue word (or letter) and the second, word (letter) were identical. In distractor trials in the letter condition, the letter presented second did not match the cue. In distractor trials for the word condition, one letter was switched in the second stimulus, and while it no longer matched the first stimulus, it was still a four-letter English word. All word conditions and one of the single character conditions were centered on the screen. Unlike Houpt (2014; in press), the location of two single character conditions, five and eight-spaced conditions were also varied randomly within the four locations available in the word condition at each level of spacing though were excluded from the current analysis due to Covid protocol changes (Appendix C). In all trials, the font was FreeMono (fixed-width) presented in a size of 30 pixels height with a 0.6 ratio for width per character). All characters were white and presented against a default dark gray background (Figure 5). The order of the spacing conditions and word/signal character were randomized.

The monitor size varied by subject, therefore the letter size and spacing were standardized by setting the experimental window by pixel size and then filling the remaining monitor space with a matching gray frame. While this technique to control differences in stimulus size is helpful, it can still vary based on pixel density between screens. Although subjects were asked to maintain a specific distance from the center of the screen throughout the task, it is unlikely that this occurred (Appendix C: Covid protocol adaptions). Four-letter English words were taken from a web crawler-based corpus previously used in Houpt and Zhang (in

Figure 5.
Illustration of examples of several stimuli.
A. *B.* *C.*



Note. A. Single character condition, B. Normal spaced word condition, C. Five spaced condition.

press; Appendix D). Subjects completed a background questionnaire (Appendix F), three subtests from the Wechsler Individual Achievement Test – Third Edition (WIAT III), five subtests from the Wechsler Adult Intelligence Scale - Fourth Edition (WAIS IV), and one subtest from the Woodcock-Johnson -Second Edition (WJ II), with adapted presentation and composite score calculations (Appendix F, G, and H). Additionally, they completed a background questionnaire (Appendix E) and the Reading History Survey (Lefty, 2000).

Procedure

For the first session, subjects met with the experimenter on a secure online meeting platform (WebEx). The experimenter reviewed the consent form, completed the background questionnaire, set the appointment for session 2, and sent subjects their subject ID and the links for the online task. Subjects received oral and written instructions prior to starting the task and asked to be as accurate as possible. Subjects also reviewed the visual angle control procedure with the experimenter which was also in the written instructions online prior to each spacing condition. According to the viewing control procedure, subjects covered one eye and extended their arm directly between the center of their face aligned with the center of their screen. Then, they were asked to adjust their viewing distance, so that their thumb covered an eight-letter width line on the center of the subject's monitor. Subjects were asked to remember that position and retain that position for each condition during each session. Subjects were advised to take a 5-to-10-minute break between the conditions. The experimenter remained on the WebEx meeting with the subjects, muted with the camera off, while the subjects completed the task in case the subjects ran into any issues.

The subjects were asked to determine if the second stimulus matched or did not match the first stimulus (Appendix D). Their responses were documented via dichotomous button selection on the keyboard ("m"=match "x" = not a match). Each block contained 175 trials, target and distractor trials were randomly ordered. A trial began with a word or letter stimulus presented for 1000 milliseconds, then a mask appeared for 200 milliseconds directly below as a visual cue for the upcoming target/distractor. The target or distractor was displayed for 1000 milliseconds. As soon as the target or distractor appeared, the subject had 2500 milliseconds to respond via dichotomous button selection. Subjects did not receive feedback on their accuracy or response time. In the three blocks of the single letter condition, the stimuli and the target/distractor followed the same procedure and spacing location changes to verify there was not an effect of the location of the distractor.

Session 2 was also on a secure WebEx meeting platform and subjects had video and audio active at all times. This session consisted of eight subtests from Wechsler Individual Achievement Test – Third Edition (WIAT III), Wechsler Adult Intelligence Scale - Fourth Edition (WASI IV), Woodcock-Johnson -Second Edition (WJ II), background survey (Appendix G and H), and the Reading History Survey (Lefty, 2000). The WIAT III subtests were those selected by Pearson for the Dyslexia Index: Spelling, Pseudowords, and Oral Reading Comprehension. WASI III subtests were Similarities, Digit Span, Matrix Reasoning, Symbol Search (modified so cannot be normed - projected and subjects wrote on screen with mouse), and Visual Puzzles. Rapid Picture Naming was given from the WJ II. All subtests that required the subject to see the stimulus book were projected via webcam. Subjects were asked to type responses to the Spelling task into the chat box and told not to correct mistakes. Symbol Search was also modified; the response sheet was projected, and subjects wrote on the screen with their mouse. All other procedures followed the manuals provided by the test manufacturers, including the order of the subtests within a test battery. The order of the three test batteries was randomized. The Reading History Survey was given after the subtests were completed.

Data cleaning

Due to a programming error in the experimental task, the response window was 2500ms rather than 1600ms as in Houpt (2015). All responses over 1600 ms were removed, which was approximately 1.5% of the centered single letter trials, 0.9% of the varied position character trials, and 1.1% of the word trials totaling 1.1% or 430 trials out of 40840.

Analysis

All analyses used R software. The SFT package (Houpt et al., 2013) was used for the workload capacity analysis. For this analysis, a baseline model (Unlimited Capacity, Independent, and Parallel-UCIP) was constructed using the single character condition (in the literature for SFT, this is referred to as a single channel) to compare with the whole word (holistic) processing. The accurate single-letter condition response time and the accuracy rate were used to create a cumulative reverse hazard function (CRHF) using the Aalen Nelson estimator. The Assessment Function used both accurate and inaccurate responses. It outputs the proportion of the product of the number of channels in the word conditions (four letters) and the single channel CRFH (4*single channel) over the word CRHF, i.e. the predicted performance via the single channel condition configural task performance over the RT time window. The Assessment Function can produce subject and group level analyses (CRHF for each subject and by group). If the proportion assessment function is greater than one, it is categorized as super capacity and if it is less than one, it is limited. Functional Principal Component Analysis was used to reduce the assessment functions to the minimum number of components possible while explaining as much of the variance in the functions as possible. These components will be used in the testing of Hypotheses 3 and 6. First, a functional eigen analysis produced a scree plot to show the number of base functions (x-axis) with the contribution of explained variance (y-axis). Then the fPCA identified the information in the functions across all subjects and conditions with the criteria of using an orthogonal basis and explaining as much variance as possible. The cognitive and achievement test subscores were used to predict the components. Finally, the capacity function, and the accurate target responses were converted to CRHFs which can also be reduced to z-scores and empirically categorized as limited, unlimited (null), and super capacity.

Bayesian hierarchical modeling was utilized to assess support for the hypotheses and post hoc analyses. The scale of evidence for the Bayesian analysis matches the criteria used in Houpt (2015), as provided by Jeffery (1961; < 0.01 decisive evidence against, <0.1 to .31 strong support against, 0.32 to 1 minimal evidence against, 1-3.2 minimum/weak support, 3.3-10 substantial/moderate support, 10 to 100 strong evidence, > 100 decisive/very strong support.

For hypotheses 1,2,3, and 6, workload capacity coefficients' z-scores and the assessment component scores are calculated from the target trials. The assessment functions (CRHF) were reduced by sub-condition for each subject to the median scores, then used to calculate z-scores to empirically categorized each subject's processing as limited, unlimited (null), and super capacity. For Hypotheses 3 and 6, the assessment functions (R SFT package assessment Group()) for each subject's sub-conditions were used in a Functional Principal Components Analysis to reduce the data. The components are ordered by the greatest degree of orthogonal compliance to the independent variable (Borsboom, 2006). These components were included in the Bayesian hierarchical modeling to determine the effect of group in the eight-spaced condition for Hypothesis 3, and with the traditional psychometric cognitive and achievement standardized subtest scores for Hypothesis 6. All word trials, accurate/inaccurate, and targets/distractors were used in Hypothesis 4. Accurate distractors were used to test Hypothesis 5.

Results

Demographics

In the reading history survey, 95% of the dyslexics and 5% of controls reported regularly leaving out articles, propositions, and pronouns when writing first drafts of papers, emails, and text messages. Additionally, 85% of the dyslexics and 0% of controls reported regularly putting words and phrases out of order (not following typical orthography/grammar structures) when writing first drafts of papers, emails, and text messages. The estimated general intelligence score (eGIS in Appendix G) was 115.6 (SD= 12.3) for dyslexics and 104 .1 (SD=15.6) for controls. The WIAT III Dyslexia Index manual states "Grades 2-12+ correctly classify 95% of students with dyslexia and 68% of controls" (Breaux, 2018). Based on the WIAT III Dyslexia Index Summed Score (the summation of Spelling, Pseudoword, Oral Reading Fluency standardized scores) and using the most aggressive identification < 90 standard score criteria (and including interpretation of the standard error), six dyslexics and no controls were classified as elevated risk (five of the "elevated" dyslexics were within the 90% CI standard error of low), three dyslexics and one control were categorized as moderate (none were within the standard error of elevated), six dyslexics and no controls were categorized as high (two dyslexics within the 90% CI standard error of low), and five dyslexics and no controls were categorized as very high (four dyslexics within the 90% CI standard error of low). Only one control was categorized as moderate, and one control was within the standard error of the elevated.

Lefty's Reading History survey correctly identified 20 out of 20 dyslexics (M= 62.8, SD= 10.0) and five out of twenty controls (M=20.2, SD= 8.8) using the suggested criterion of 0.30. Seventeen out of twenty dyslexics and five out of 20 controls reported family history of dyslexia/reading issues without a formal diagnosis. The questions that had the best overall indication of dyslexia diagnosis were "Did you have difficulty learning letter and/or color names when you were a child?" and, "Did your parents ever consider having you repeat any grades in school due to academic failure (not illness)" (indicating the lack of proper early interventions for these future college-bound students). Only nine out of the 20 dyslexics in this study received reading interventions in primary or secondary school.

Hypothesis 1: Super capacity for all subjects in the normal spaced conditions.

Results indicate slow processing and low accuracy in both groups. Capacity coefficient z-score statistic (Houpt & Townsend, 2012) showed that only six out of forty subjects (three dyslexic) were at supercapacity for the normal-spaced condition (Table 1). Thus, even at the most basic task, four letter word reading without spacing, this research did not replicate the results of supercapacity as in Houpt et al., (2015; 2012) or Houpt and Zhang (in press). In both groups, the accuracy was often lower than the 95% criteria set for use of the capacity coefficient in (Houpt, et al., 2012). Of the dyslexics, six of the 20 normal spaced condition, eight out of 20 in the five-spaced, and twelve out of 20 in the eight-spaced condition were below .90 accuracy.

Table 1
Capacity coefficient z-score by Group.

Controls

Descriptive statistics:	*Mean*	*SD*	*Range*	*Capacity:* *Super*	*Unlimited*	*Limited*
0 Spaced	1.73	0.19	0.69	3	17	0
5 Spaced	1.58	0.16	0.68	1	19	0
8 Spaced	1.52	0.21	0.83	1	19	0

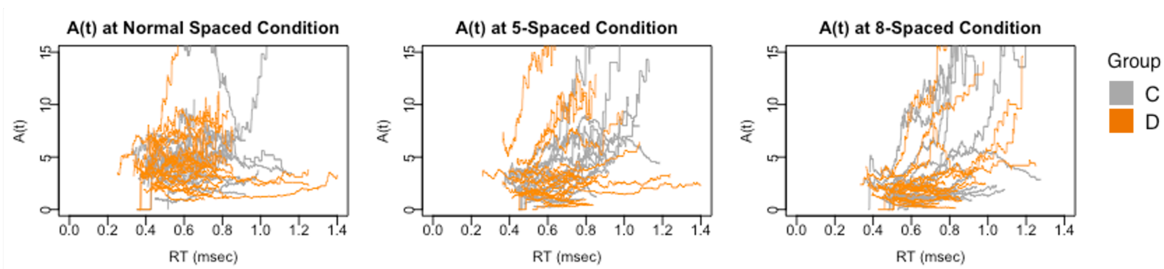
Dyslexics

Descriptive statistics:	*Mean*	*SD*	*Range*	*Capacity:* *Super*	*Unlimited*	*Limited*
0 Spaced	1.74.	0.21	0.78	3	17	0
5 Spaced	1.56	0.17	0.72	1	19	0
8 Spaced	1.46	0.15	0.76	2	18	0

Note. Poor differentiation of capacity across the conditions

Of the controls, six of the 20 in the normal-spaced condition, four out of 20 in the five-spaced, and six out of 20 in the eight-spaced condition were below .90 accuracy. Unlike the capacity coefficient which assumes greater than 95% accuracy and only uses correct trials, the assessment coefficient accounts for the accuracy rate and uses both correct and incorrect trials. Given the lower accuracy rate for redundant targets in this data, especially in dyslexics, the assessment function is a more appropriate analysis. Visual inspection of the assessment function (Figure 6)

Figure 6.
Assessment function for each Spaced Condition by Group.



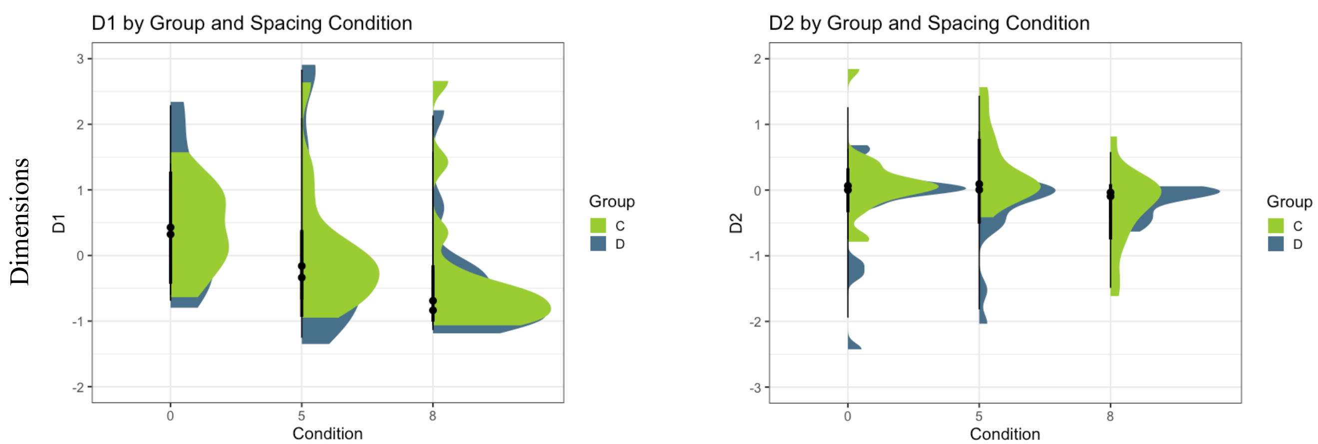
Note. Plot shows poor differentiations by group and overall lack of qualifiable trends. Visual inspection shows a reduction of capacity as intra word spacing increases. The majority of the subjects are performing at unlimited capacity.

shows more efficient processing (supercapacity > 1) across both groups for the normal-spaced condition. The five-spaced condition showed a reduction in efficiency. And the eight-spaced condition showed the most uniform performance across subjects as unlimited (A(t) =1) or limited (A(t) <1). This visual inference is supported by the following analysis which reduced the assessment functions into orthogonal dimensions. These dimensions were then predicted by group status and spacing condition

Group effects were absent. From the fPCA of the assessment coefficient, two dimensions accounted for 80% of the variation in the base functions. Neither of these dimensions gave evidence of group effects (Figures 7 and 8); D1 (first of two dimensions from the fPCA) had strong support for spacing condition and subject, (D1~ Condition + Subject over Subject only model), BF= 1931, and moderate evidence against Group , BF=.45 (D1~ Condition + Group+ Subject over the best model). There was also strong evidence against the Group by Condition

Figures 7 and 8.

Density of fPCA Components for Subjects by Group across Spacing Conditions.



Note. The density functions of the component score show a skewed though largely uniform distributions for both Groups across the Conditions.

interaction, BF=0.31, over the strongest model without it, D1~ Condition + Group+ Subject. The second dimensions, D2, had weak evidence across all models. The strongest model had moderate support against the inclusion of Group over the Subject only model.

Hypothesis 2: Super capacity for controls and dyslexics with high IQ, phonetic, and coding scores cluster and unlimited capacity for all other dyslexics in the fivefold intraword spacing condition

Processing was too slow to test hypothesis. Only one subject, a dyslexic, had a capacity coefficient z-score at supercapacity for the five-spaced condition. All other subjects were at unlimited capacity for the five-spaced condition.

Hypothesis 3a: Unlimited capacity for controls and limited capacity for dyslexics at the eightfold spacing condition.

Two controls and one dyslexic's capacity coefficient (C(t)) were empirically found to be at supercapacity while the others were at unlimited capacity for the eight-spaced condition; none of the subjects were at limited capacity (Table 1).

Hypothesis 3b: There will be strong support for the main effect of group in the eightfold conditions.

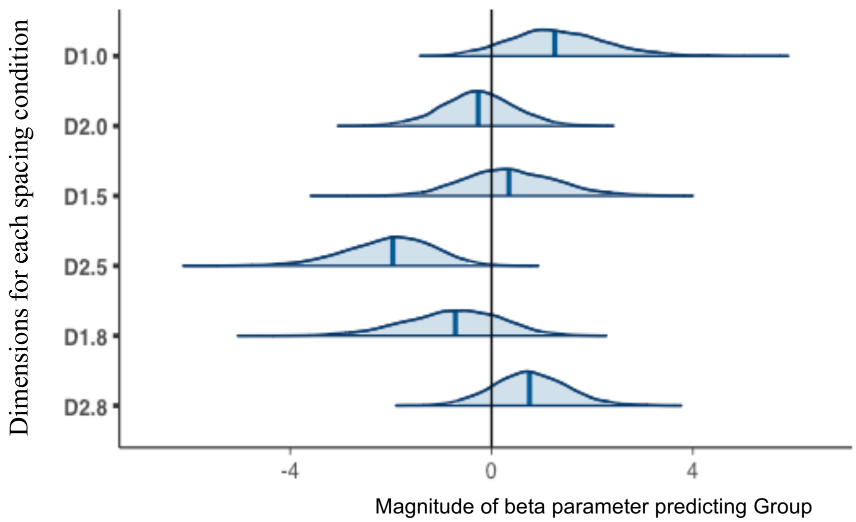
Strong support *against* group effects. For the eight-space condition, there was strong support against the effect of Group, BF(D1) = 0.3 and BF(D2)=0.3. The relative influence of the by spacing condition when predicting group showed poor differentiation by spacing condition though a slight influence of the later second component for the five-spaced condition (Figure 9 and Table 2).

Table 2

Posterior Means and HDI for fPCA components for each spacing condition predicting Group

	Posterior Mean	HDI 2.5%	HDI 97.5%
D1.0	1.26	-0.42	3.35
D2.0	-0.27	-1.75	1.21
D1.5	0.35	-1.37	2.39
D2.5	-1.96	-4.03	-0.47
D1.8	-0.72	-2.84	0.98
D2.8	0.75	-0.66	2.32

Figure 9.
Beta parameter distribution variations of the fPCA components for each Spacing Condition predicting Group.



Note. D1.0 and D2.0 are the first and second component for the normal spaced condition. D1.5 and D2.5 are the first and second component for the five- spaced condition. D1.8 and D2.8 are the first and second component for the eight-spaced condition. There is poor differentiation between components at every spacing condition when predicting Group.

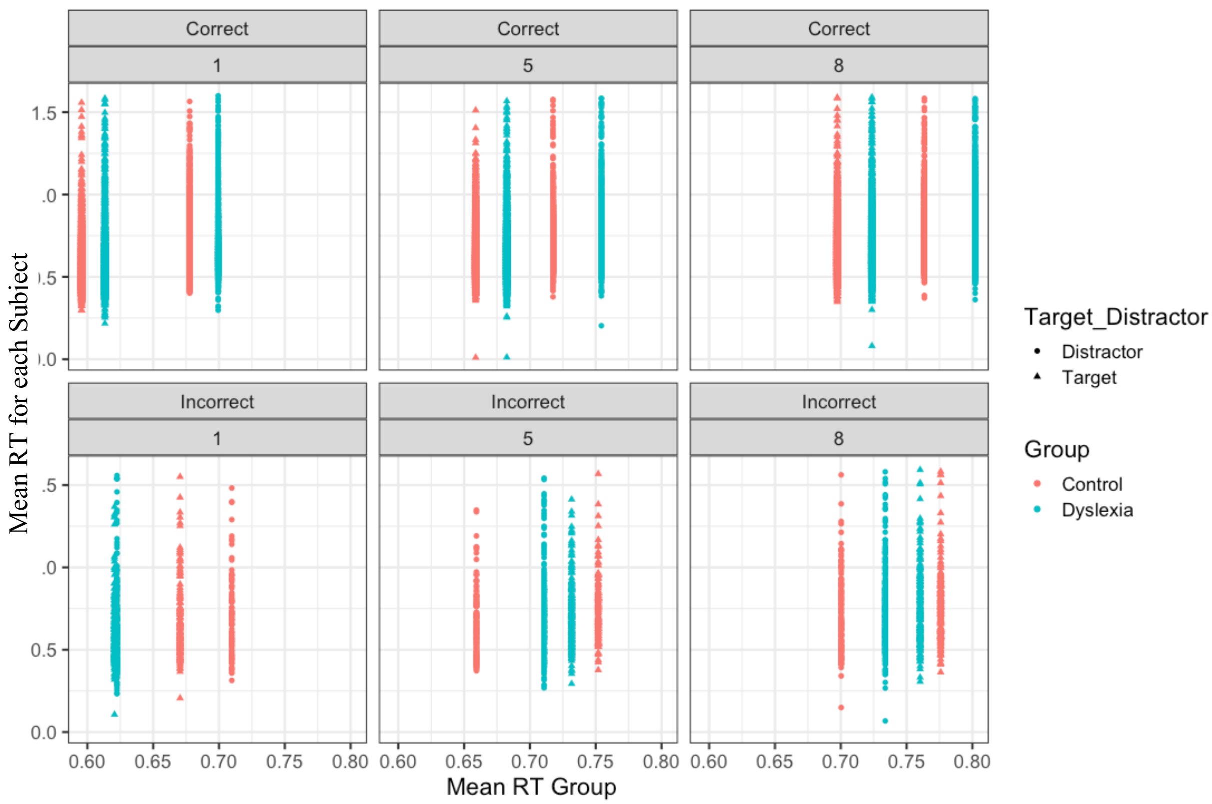
Hypothesis 4a: The mean response time will show strong support for main effects of group, spacing, and target/distractor(TD).

Violation of assumptions for parametric analysis. For raw response time, a visual inspection of the residuals via qq-plot revealed a violation of normality. A Brown-Forsythe test was significant indicating a violation of homogeneity of variance ($F(1,20361)=112.5$, $p<0.001$) as well. A Durbin-Watson Test showed the errors are not independent as expected with repeated measures (ar= 0.36, D-W =1.29, $p<0.05$). Rather than risk distorting the power or likelihoods of Type I or II errors (Figure 10), Bayesian inferential and predicative hierarchical modeling techniques (STAN and Bayes.Factor Package) were used to describe the data.

Weak effect of group for RT. As the a priori hypothesis did not specify if the responses were accurate, inaccurate or both, all responses, both accurate and inaccurate responses, were included to account for all possible factors. Accuracy was modeled with spacing conditions, target/distractors, and group to predict response time with Bayesian hierarchical methods. The best model included the main effects of Group, Condition, and Target/Distractor (see Figure 10). Specifically, the best model was Mean RT~ Group + Condition + TD, BF=5e10, over the

Figure 10.

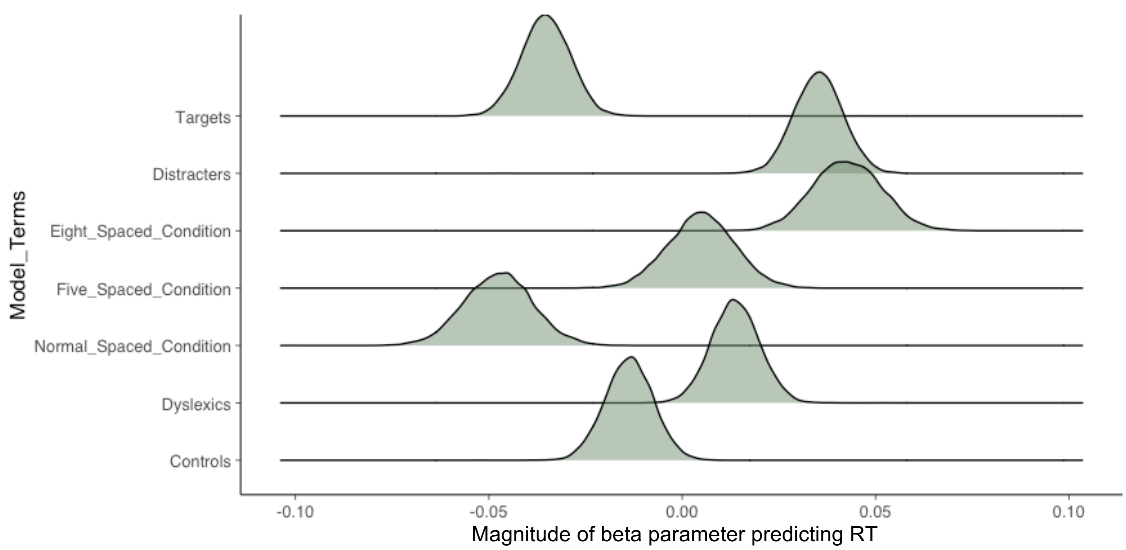
Mean Response Time (x-axis) for Group by Mean Response Time for each Subject (y-axis) in all Conditions with Accuracy (factor) for Targets and Distractors.



Note. Figure shows minor differences in RT between Groups for Correct versus Incorrect responses. The pattern of responses visualized in the Group by Target/Distractor interaction while predicting Accuracy is largely explained by the Dyslexics' Incorrect Distractors. This visualization also highlights the overall lack of effect of Group when predicating Response Time (RT).

intercept-only model. Group was the weakest term, BF=1.5 over the next best model which did not contain Group (Mean RT~ Condition + TD) (Figure 11). Marginal posteriors of coefficient for the model Mean RT~ Group + Condition + TD). The third best model, (Mean RT~ Group + Condition + TD + Group:TD) had strong evidence against the Group:Target/Distracter

Figure 11.
Beta parameter distribution variations in Group, Conditions, and Target/Distractor when predicting within subject mean response times.



Note. Targets are relatively faster than Distractors (strong influence). Controls are slightly faster than Dyslexics (weak influence). Increasing the intraword spacing increased the mean RT (positive effect of spacing).

interactions inclusion, BF=.22. The inclusion of Target/Distracter has strong support compared to the model without it, BF=506344. The inclusion of Condition has strong support compared to the model without it, BF=704572. In general, for the strongest model (Mean RT~ Group +

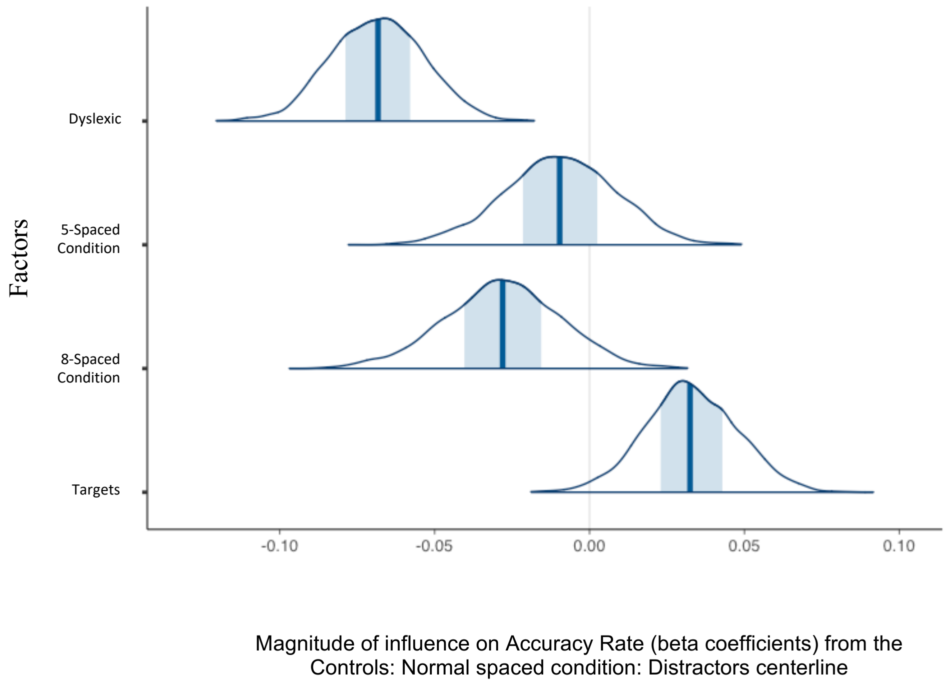
Table 3

Posterior Means and HDIs Intervals for model Mean RT~ Group + Condition + TD

	Posterior Mean	HDI 2.5%	HDI 97.5%
Control	-0.0136	-0.0258	-0.0014
Dyslexic	0.0136	0.0014	0.026
Condition-0	-0.0474	-0.065	-0.030
Condition-5	0.0047	-0.012	0.022
Condition-8	0.0427	0.0256	0.060
Distractor	0.035	0.0229	0.047
Target	-0.035	-0.047	-0.023

Condition + TD), controls are faster than dyslexics, target trials are faster than distractor trials, and the quickest condition is the normal-spaced, and the longest the eight-spaced condition (Figure 12 and Table 3).

Figure 12.
Marginals of the predicted posterior for the model Accuracy~ Group + Condition + Target/Distractor.



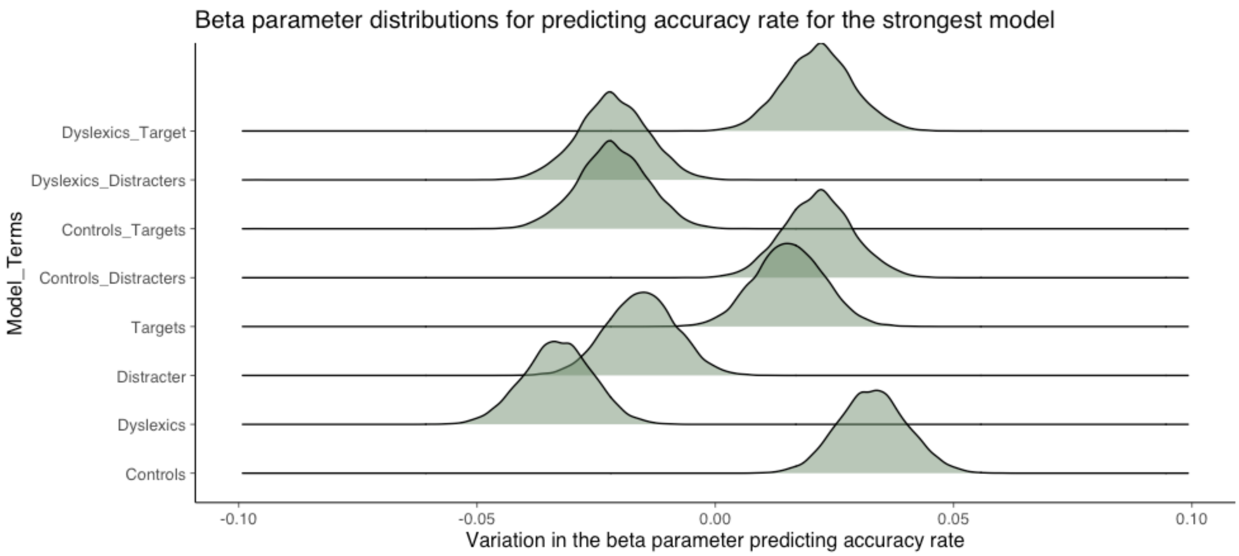
Note. The relative influence of the factors on Accuracy Rate as compared to Controls: Normal Spaced: Distractors. The terms with the least overlap were Group and Target/Distractor.

While the strongest model matched the predicted model, the evidence to support group is the most important factor to show discrimination in the task and it was not present.

Hypothesis 4b: The accuracy rate will show positive support for full model space, group, target/distractor three-way interaction.

Group status was the strongest predictor of accuracy (Figure 12). The model with the most support is Group + Target/Distractor + Group:Target/Distractor, BF= 60796 (Figure 13 and Table 4) over the intercept only model and BF= 7.3 over the next best model (Group + Condition + Target/Distractor + Group: Target/Distractor). This is surprising considering Condition was consistently an included factor in the response time models and shows that the intraword spacing manipulations did not affect accuracy. The Group:Target/Distractor interaction had strong evidence, BF =18.7, over the model without the interaction. Group had the strongest main effect, BF= 2652 over the model with just Target/Distractor. The main effect of Target/Distractor had

Figure 13.
Beta parameter distribution variations in Group + Target/Distractor + Group:Target/Distractor when predicting within subject Accuracy Rates.



Note. The Group:Target/Distractor interaction shows dyslexics are less accurate on distractors and controls are less accurate on targets.

weak support, BF= 1.5 over the model with just Group. The main effect of Group had very strong support, BF= 2669, over the Target/Distractor only model.

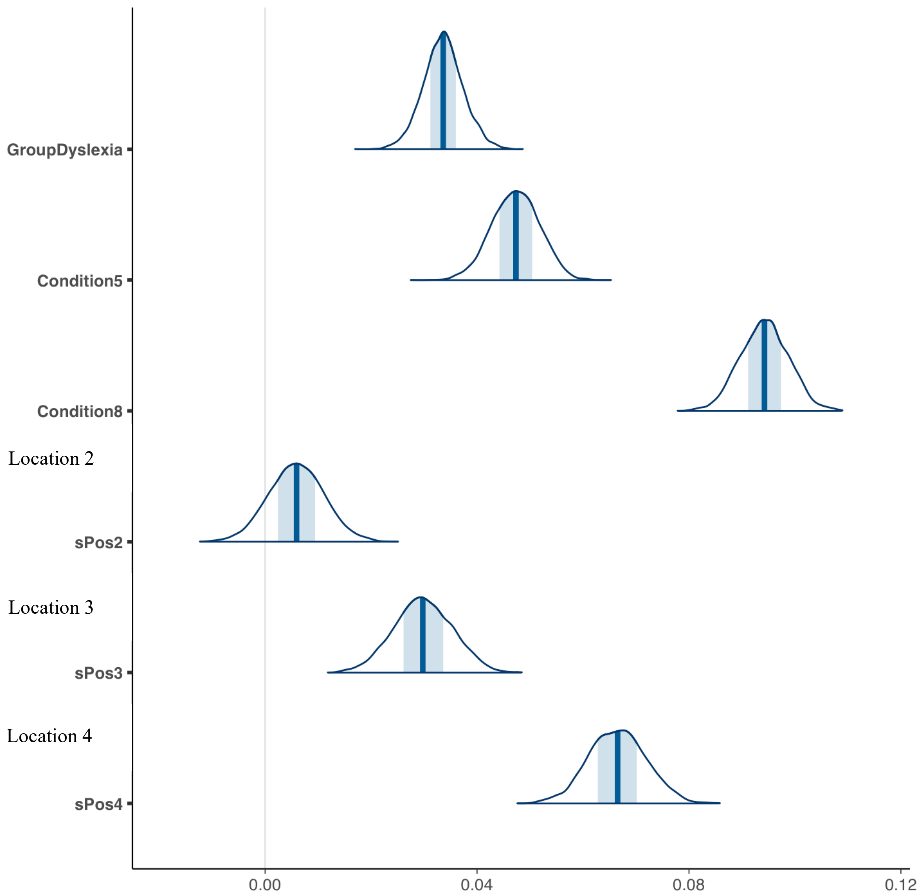
Table 4
Posterior Means and HDIs Accuracy Rate~ Group + Target/Distractor + Group:Target/Distractor

		HDI	
	Posterior Mean	2.5%	97.5%
Group	-0.109	-0.149	-0.070
Target/Distractor	-0.013	-0.052	0.027
Group: Target/Distractor	0.087	0.033	0.143

Post hoc: Removing outliers. The same analysis was repeated without the outliers to make sure they did not impact the results. Two subjects had below an average 80% accuracy across the three condition levels (one from each group). They were removed as well as the two subjects who were identified as outliers in the assessment function. The model with the most support was still Group + Target/Distractor + Group:Target/Distractor with very strong support,

Figure 14.

Marginal posteriors of coefficient for the model Group + Condition + Location when predicting RT



Magnitude of influence of factors in relation to Controls: Normal Spaced Condition: 1st Location predicting RT

Note. The influence of each factor is scaled in comparison to the vertical line that represents the default factor Controls: Normal Spaced Condition: 1st Location when predicting RT. This shows when considering the Location effects, there is support for the simple main effects of Group, Condition, and Location

BF= 3.7e6 over the intercept-only model, though only moderate support when compared to the next model (Group + Condition + Target/Distractor + Group:Target/Distractor), BF=4.

Identifying within-subject variation as a nuisance variable did not remove group effects. The original analysis was repeated (including outliers) with Subjects as a random intercept. The results agreed with the original analysis though the strength of the evidence was reduced once the within-subjects variation was accounted for with the random intercept, Accuracy ~Group + Target/Distractor + Group: Target/Distractor + Subject, BF=11654, over the intercept only model. It also had moderate evidence, BF=4.1, over the second strongest model, Accuracy~ Group + Condition + Target/Distractor + Group: Target/Distractor + Subject. Overall, these results suggest that the lack of support for the inclusion of spacing condition in the strongest model found for the a priori hypothesis is due to the influence of an unknown external variable, that is shared by the dyslexic group though not manipulated by intraword spacing.

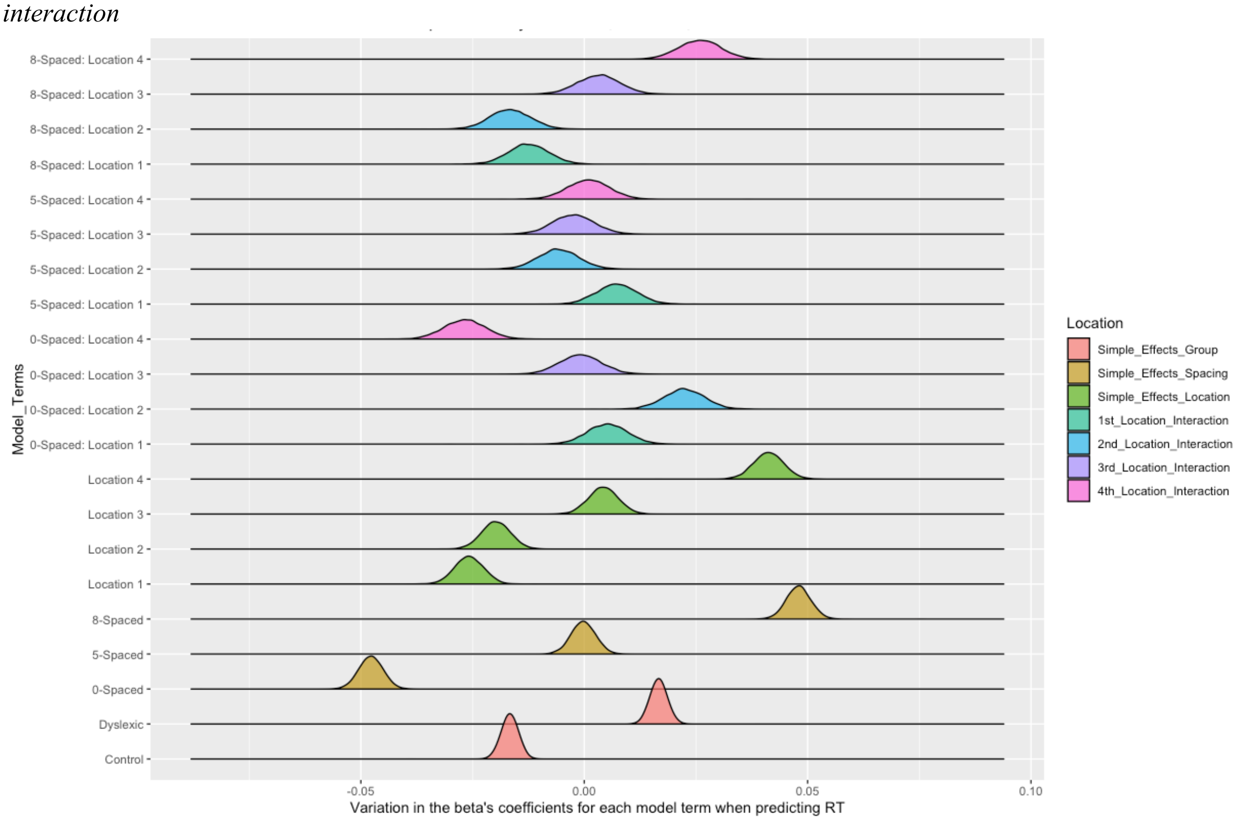
Post hoc frequentist test. Accuracy fully mediates the relationship between Target/Distractor and Group. Basic frequentist tests and mediation analysis were used to examine the lack of effect of spacing condition in the previous analysis, the three-way interaction of Accuracy, Test (single-character, varied position character, and word trials), and Target/Distractor predicting Group found Accuracy in the distractor trials were a significant predictor of Group in the center single character ($b=0.58$, $p<0.01$) such that dyslexics had more inaccurate responses than controls.

***Hypothesis 5:* There will be strong support for the best model of group, location, and spacing for the accurate responses of the distractor trials.**

Effect of Group, Spacing Condition, and Location and interaction of Location and Spacing Condition. There was support for the simple main effects of Group, Condition, and Location (Figure 14). The strongest model is RT~ Condition + Location + Condition:Location + Group, BF= 5.5e137 compared to the intercept only model. When compared to the next best model, (RT ~ Condition + Location + Condition:Location + Group + Condition:Group), RT~ Condition + Location + Condition:Location + Group had strong support, BF=38. The greatest effect was found in spacing Condition (BF=9.0e84 over the model without), then Location (BF=6.1e42 over the model without), followed by Group (BF=1.7e15 over the model without), and finally the condition by location interaction (BF=8.1e6 over the model without). See Figure 15 for the full

Figure 15.

The coefficient distributions for the RT predicted by Group, Spacing Condition, Location, and Condition:Location interaction



Note. The greatest effect was found in with spacing condition, then position, followed by group and finally the condition by location interaction.

model and the strongest model in Figure 16 with the posterior means and HDI in Table 5. While there was a main effect of Group, there was decisive evidence against the addition of the Group:Location interaction, BF=0.02, negating the hypothesis.

Table 5.

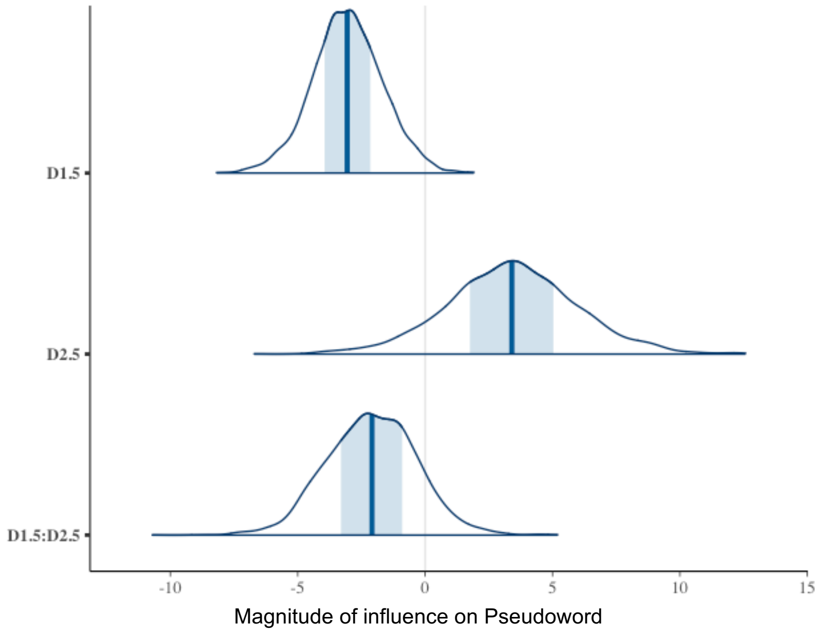
Posterior Means and HDIs RT~ Condition + Location + Condition:Location + Group

	Posterior Mean	HDI 2.5%	HDI 97.5%
Condition-1	-0.048	-0.053	-0.043
Condition-5	-0.0001	-0.005	0.005
Condition-8	0.048	0.043	0.053
Location-1	-0.026	-0.032	-0.019
Location-2	-0.0197	-0.026	-0.013
Location-3	0.004	-0.002	0.011
Location-4	0.041	0.035	0.048
Group-Control	-0.017	-0.020	-0.013
Group-Dyslexia	0.017	0.013	0.020
Condition-1			
Location 1	0.005	-0.0036	0.014
Location 2	0.022	0.0135	0.031
Location 3	-0.0008	-0.0098	0.008
Location 4	-0.027	-0.036	-0.018
Condition-5			
Location 1	0.007	-0.0015	0.016
Location 2	-0.0058	-0.015	0.003
Location 3	-0.0025	-0.0115	0.0064
Location 4	0.0009	-0.008	0.0101
Condition-8			
Location 1	-0.0126	-0.021	-0.0036
Location 2	-0.0165	-0.025	-0.0075
Location 3	0.0033	-0.006	0.0126
Location 4	0.0258	0.017	0.035

Hypothesis 6a1: In five-spacing conditions, a dyslexic's response time and accuracy rate will predict scores on Wechsler Individual Achievement Test (WIAT) phonetic awareness, verbal working memory (Digit Span), and coding (tests sensitive to temporal processing Symbol Search and Rapid Picture Naming).

The hypothesis was ambiguous concerning the predictors, e.g. RT single responses, the mean, the median, or as it is represented in the fPCA components from the assessment function. The strictest compliance to the a priori hypothesis as written is individual RT, which introduces bias. The disproportional number of samples in a factor within a Bayesian model will artificially strengthen the smaller sample; the accurate rate is a single score and RT has approximately 175 samples per trial per subject. The results for the RT with accuracy as the dimensions from the assessment function's fPCA (D1.5 as the first dimension from the fPCA for the five-spaced condition and D2.5 as the second dimension from the fPCA for the five-spaced condition), as in Houpt et al. (2015). Using the assessment coefficient dimensions produces more valid, and

Figure 16.
Marginals of the predicted posterior for the model Pseudoword~ D1.5 + D2.5 + D1.5:D2.5 for the five-spaced condition for dyslexics (n=20)



Note. The relative influence of the factors predicting Pseudoword showing weak effect of D1.5 and poor discrimination across all other factors.

stringent, results as they include both factors, represent the processing efficiency controlling for individual differences in capacity, and does not artificially inflate the results with sample size differences. The dimensions results are included post hoc. The psychometric tests predicting the Assessment function components were also modeled post hoc**.**

Phonetic awareness subtests

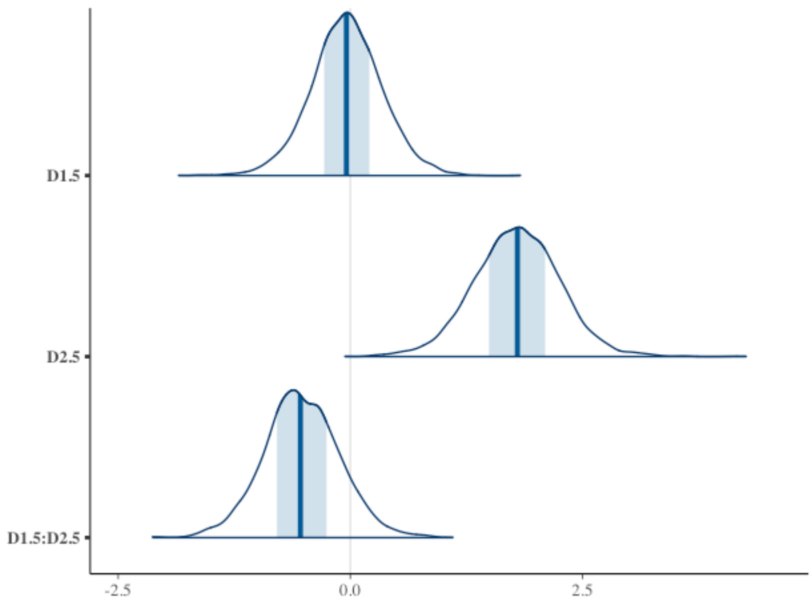
Pseudoword Subtest

The individual RTs with accuracy rate and assessment coefficient dimensions models did not support the predictive validity of response time for the Pseudoword subtest score.

Individual RTs**.** Neither response time with accuracy rate predicted Pseudoword normed score; the best model was accuracy rate over the intercept only, BF= 0.13.

Post Hoc: Components from Assessment fPCA. There was weak evidence for the best model, D1.5 over the intercept only, BF=1.76, when predicting Pseudoword (Figure 17).

Figure 17.
Marginals of the predicted posterior for the model Symbol Search~ D1.5 + D2.5 + D1.5:D2.5 for the five-spaced condition for dyslexics (n=16)



Note. The relative influence of the factors predicting Symbol Search shows that D2.5 has the strongest influence on the dependent variable.

Spelling Subtest

While the more biased analysis using Individual RTs with accuracy rate showed strong evidence, the assessment coefficient dimensions models did not support response time and accuracy rate in the five-spaced condition as predictors of modified WIAT III Spelling.

Individual RTs. There was very strong evidence for the best model of RT + Accuracy Rate +RT*Accuracy Rate, BF=6e125 over the intercept-only model (RT: Posterior Mean = 17.0, 95% HDI = [16.9, 38.5]; Accuracy Rate: Posterior Mean = 57.7, 95% HDI = [57.7, 65.0]; RT * Accuracy Rate: Posterior Mean = -51.3, 95% HDI = [-51.0,-52.2]). Compared to the next strongest model, Accuracy Rate only, the best model also had very strong evidence, BF=927. RT*Accuracy Rate interaction was the strongest factor of the model and the interaction term.

Post Hoc: Components from Assessment fPCA. There was minimum evidence for within-subject median RT or accuracy rate predicting modified Spelling subtest score; the best model was accuracy only, BF= 0.39 over intercept.

Verbal Working Memory Subtest

Digit Span Subtest

While the more biased analysis using the Individual RTs with accuracy rate showed strong evidence, the assessment coefficient dimensions models did not support response time and accuracy rate in the five-space condition as predictors of the Digit Span subtest score.

Individual RTs. There was very strong evidence for the best model of RT + Accuracy Rate +RT*Accuracy Rate, BF=3.8e28 over the intercept-only model (RT: Posterior Mean = 12.1, 95% HDI = [10.0, 14.2]; Accuracy Rate: Posterior Mean = 10.2, 95% HDI = [8.0, 12.3]; RT * Accuracy Rate: Posterior Mean = -16.2, 95% HDI = [-19.1,-13.5]). Compared to the next strongest model, Accuracy Rate only, the best model also had very strong evidence, BF=8.7e24.

Post Hoc: Components from Assessment fPCA. There was minimum evidence for D1.5, D2.5, or their interaction for predicting Digit Span subtest score; The best model was D2.5 only, BF= 2.7 over intercept.

Coding (Visual Processing) Subtests

Symbol Search Subtest

Support for visual information processing in the five-spaced condition. Five of the dyslexic subjects did not complete the Symbol Search subtest because they could not correctly understand the instructions (two of the four subjects) or used a browser that did not properly interface with WebEx. All three analyses supported the use of response time and accuracy in the five-spaced condition to predict Symbol Search subtest standardized scores.

Individual RTs. There was strong evidence for the best model of Accuracy Rate, BF=1.9e206 over the intercept-only model (Accuracy Rate: Posterior Mean = 10.2, 95% HDI =

[8.08, 12.38]). Accurate rate only model also had strong evidence over the next strongest model, RT+ Accuracy Rate, BF=25.9.

Post Hoc: Components from Assessment fPCA: D2.5 was the strong predictor of the Symbol Search subtest. When predicting the Symbol Search score, there was strong evidence, D2.5 only, BF= 14,016 over the intercept only (Figure 18 and Table 6). The best model, D2.5 only, had weak evidence over the second model, BF(D1.5 + D2.5 + D1.5:D2.5)= 1.2, and third model, BF(D1.5 +D2.5)=1.9. It had strong evidence over the remaining model, BF(D1.5)=13,010. The analysis was repeated for controls only with the strongest model, D1.5 only, had minimal evidence against its inclusion, BF=0.43 over intercept only. The D2.5 only model was compared to the strongest model, D1.5 only, and there was minimal evidence against it, BF=1.0.

Table 6
Posterior Mean and HDI for D1.5, D2.5, and their interaction term predicting Symbol Search in dyslexics

	Posterior Mean	2.5%	97.5%
D1.5	-0.04	-0.48	0.43
D2.5	1.66	1.05	2.25
D1.5.&.D2.5	-0.995	-0.999	0.01

Rapid Picture Naming (RPN) Subtest

RPN is part of the WJ II. It is a test of cognitive fluency and processing speed related to phonetic retrieval of lexical information based on the coding of a visual image. While the more biased analysis using individual RTs with accuracy rate showed strong evidence, the assessment coefficient dimensions models did not support response time and accuracy rate in the five-spaced condition as predictors of RPN.

Individual RTs. There was very strong evidence for the best model of RT + Accuracy Rate +RT: Accuracy Rate, BF=5.7e5 over the intercept-only model (RT: Posterior Mean = 28.4, 95% HDI = [11.7, 44.8]; Accuracy Rate: Posterior Mean = 42.3, 95% HDI = [23.6,58.3]; RT:Accuracy Rate: Posterior Mean = -37.8, 95% HDI = [-60.1,-16.3]). Compared to the next strongest model, Accuracy Rate only, the best model had weak support, BF=1.28. There was strong support for the best model when compared to RT + Accuracy Rate model, BF= 21.6.

Post Hoc: Components from Assessment fPCA. There was minimum evidence for D1.5, D2.5, or their interaction for predicting the RPN subtest score.

Post hoc: All subtest scores predicting D1.5 and D2.5

For dyslexics only, and without the five subjects that did not complete the Symbol Search, the strongest model for D1.5 was Pseudoword + Symbol Search, which had moderate support, BF=4.1, over the intercept-only model. It was very similar in strength to the next model, Pseudoword + Spelling + Symbol Search, BF= 3.6, over the intercept-only model. The strongest model for D2.5 was the Symbol Search subtest score only model, BF=33.2, over the intercept-only model and it had weak support, BF=2.3, when compared to the second-best model, Digit Span + Symbol Search, BF=14.6. As the moderate evidence for Pseudoword + Symbol Search subtest score is conflicting with the prior post hoc analysis, Appendix I has a further discussion on how the operating system and browser could impact RT data collection.

Hypothesis 6b: The Wechsler Adult Intelligence Scale (WAIS) and Wechsler Individual Achievement Test (WIAT) discrepancy scores will predict WAIS IQ Scores

Due to COVID-19 protocols, Full Score IQ could not be calculated using the procedures outlined in the WAIS and WIAT manuals so this hypothesis could not be tested.

Post Hoc: K-means Clustering. The k-means clustering set to two clusters to represent the groups, showed the following trends in this dataset;

1. The WIAT Spelling subtest using the normal standardized score charts correctly identified 19 out of 20 controls and 15 out of 20 dyslexics (76.7% of the within-cluster sum of squares by cluster-relatively high variation of scores within the cluster); Sensitivity = 0.75, Specificity = 0.95.

2. The Dyslexia Index (which included the Spelling subtest) correctly identified 19 out of 20 controls and 15 out of 20 dyslexics (74.4% of the within-cluster sum of squares by cluster) in the kmeans clustering; Sensitivity = 0.75, Specificity = 0.95.

3. WIAT Spelling and the estimated General Intelligence Scale (Visual Puzzles, Matrix Reasoning, and Similarities) correctly identified 17 out of 20 controls and 17 out of 20 dyslexics (49.7% of the within-cluster sum of squares by cluster); Sensitivity = 0.85, Specificity = 0.75. While the Dyslexia Index and the eGIS correctly identified 19 out of 20 controls and 16 out of 20 dyslexics and (66.9% of the within-cluster sum of squares by cluster); Sensitivity = 0.8, Specificity = 0.95.

Hypothesis 6c: The capacity component scores will not significantly predict WAIS Full IQ Scores for any subject.

Due to Covid protocols, we used the modified estimate of intelligence quotient found in Appendix G. The D1.5-only model had strong evidence against it, BF=0.35, over the intercept-only model. The full model, eGIS~ D1.0 + D2.0 + D1.5 + D2.5 + D1.8 + D2.8, had weak evidence against, BF=0.02, when compared to the intercept only model. There is little variation in the estimated intelligence scale that could be attributed to any of the components. Note there will be differences in the eGIS and an actual WAIS full score IQ (see Appendices G and H).

Discussion

Configural processing of words in dyslexics and controls were compared to the part-processing of letters with both the manipulation of first-order features (target vs distractors) and second-order properties (intraword spacing). The findings contribute to general word perception/reading theory as well as dyslexic reading and developmental theories. There are also psychometric contributions that could be included in future research.

Theory

Dyslexic word perception/reading theory

There is a logical association between WSE and logographic reading, and there is an opportunity to examine more closely when phonetic processing is not automatic in dyslexics. There is evidence that dyslexics use visual processing to process words with moderate intraword spacing in words while controls do not. These results can explain the paradoxical results of WSE in dyslexics despite very low phonetic awareness and processing scores (Grainger et al., 2003; Zeigler et al., 2008, Houpt et al, 2015). The WSE in both dyslexic and controls gives a common baseline in word processing (Grainger et al., 2003; Zeigler et al., 2008, Houpt et al, 2015). Despite the failure of Intraword spacing to differentiate the controls from the dyslexics, the finding rejects the assumption that literate dyslexics use identical modalities to process words as controls. Covid-19 protocols prohibited typical experimental controls so the results should be interpreted with caution.

For the general performance analyses, there was poor differentiation for group for RTs, capacity coefficient, and the assessment function. This confirms the prior findings by Granger et al., (2004), Zeigler et al. (2006), and Houpt et al. (2015), dyslexics have WSE and do not have poor lexical quality or word knowledge due to error monitoring as suggested by Harris, Creed, Perfetti, and Rickles (2022). Rather, and as proposed by the development model in the Introduction, dyslexics have a verbal working memory deficit, i.e. a lack of verbal working memory capacity, that prohibits the proficient manipulation and use of phonetic and verbal information. There is a reduced capacity in verbal working memory and therefore, there is inadequate information present to monitor for errors.

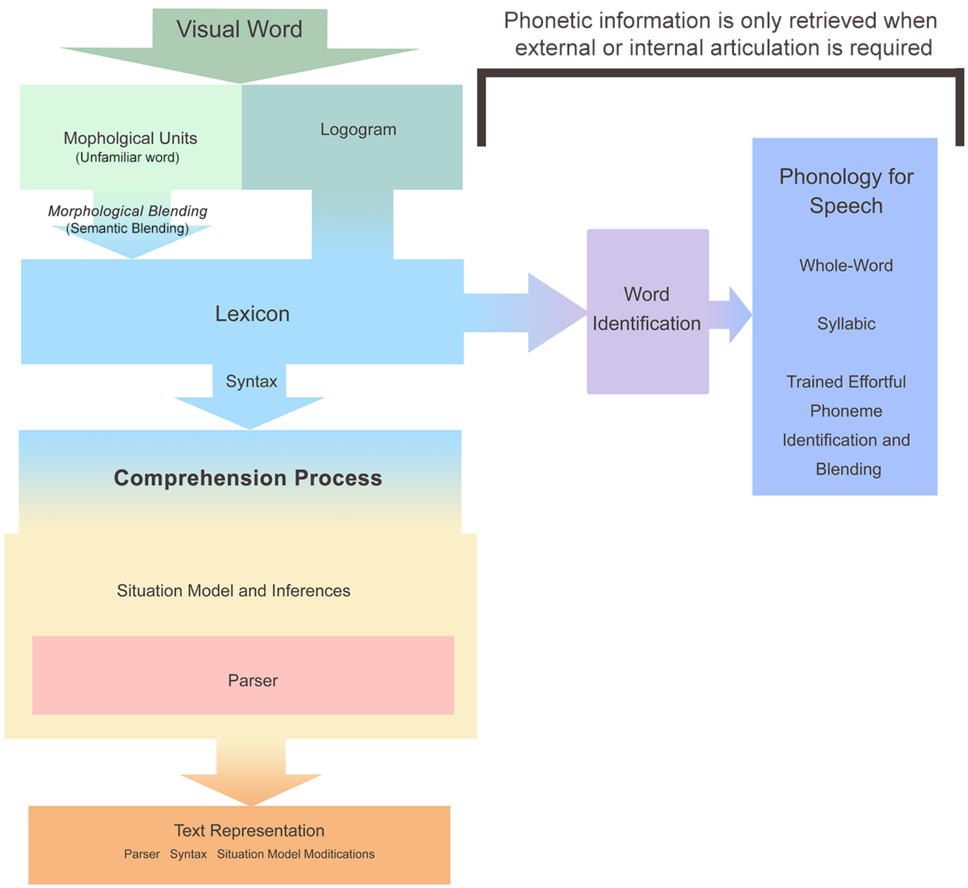
As found in Zeigler (2006), there was a group difference for accuracy of the distractors consistent across all spacing conditions. Moreover, post hoc examinations support an external factor, like a verbal working memory deficit for correct response button coding, and not a phonetic deficit as manipulated by intraword spacing, as the cause. For dyslexics, there was decisive support for the assessment coefficient's fPCA second dimension for the five-spaced condition (D2.5) as a predictor of visuo-spatial information processing and decision speed (WAIS IV Symbol Search). For controls, neither of the components from the fPCA of the assessment function for the five-spaced condition were predictors of Symbol Search subtest. And, similar to Grainger (2003), we conclude that the variance in processing between the two groups (accuracy and D2.5 component from the assessment function) was related to general working memory/executive functions and not phonetic processing.

In first-order manipulations, the recognition of targets was faster than identification of distractors for both groups and the accuracy for identification of targets was similar for both groups. However, the accuracy of distractors was reduced in dyslexics while controls had similar accuracy for both targets and distractors. For the second-order manipulation, the increase of intraword spacing increased response time in both groups, but it did not have an impact on accuracy. This reduced accuracy in distractor identification could reflect a deficit in phonological processing. Nevertheless, the post hoc analyses showed the variation in accuracy was present throughout all test conditions including the simple centered single character trials. It is therefore more likely that the data reflects a central executive deficit (reversing the dichotomous coding of which button to push - coding of “m” as correct and “x” as incorrect) (Alt, Fox, Levy et al., 2022; Gray, Green, Alt et al., 2017).

In the background questionnaire, 95% of the dyslexics and 5% of controls reported regularly leaving out articles, propositions, and pronouns when writing first drafts of papers, emails, and text messages. Additionally, 85% of the dyslexics and 0% of controls reported regularly putting words and phrases out of order (not following typical orthography/grammar structures) when writing first drafts of papers, emails, and text messages. This pattern points to the lack of automaticity in internal narration when writing (phonological loop). According to the Multiple Resource Theory (Wickens & Kessel, 1980), diverting resources from a limited capacity system will cause errors/delays in processing when compared to non-dyslexic processing. If dyslexics are diverting resources from working memory to compensate for the lack of automaticity in phonetic retrieval, these errors/delays in behaviors utilization of working memory (phonological loop) and attention resources (central executive) are expected. The finalized Dyslexia Reading Model based upon these principles and the results of Hypothesis 5 are in Figure 18.

Figure 18

Proposed Dyslexia Reading Model



Note. *Familiar words presented as visual text are processed as whole logograms which are then sent to the to the lexicon for semantic identification and then sent to the comprehension process. Unfamiliar words can be broken into morphological units for proximate semantic retrieval. If unsuccessful, morphological units will be articulated internally/externally to attempt word identification. There is a disconnect between the letters/phonemes/word identification where the dyslexic could regularly use the word though be unable to identify it as a logogram or by blending the phonemes together. Phonetic retrieval of the word is also required from reading sentences out loud which exhausts the verbal working memory and central executive resources leading to increased fluency and comprehension errors. Also, due to the compensation of central executive for the verbal working memory deficit, fluency and comprehension errors related to syntax are common. Dyslexics also read/informally write for hard semantic content and tend to skip the syntaxes words, like propositions, articles, and pronouns, because the visual-spatial working memory is also compensating for the verbal working memory deficit. Visualizing nouns, verbs, direct objects, adjectives, and adverbs is more conducive to visual-spatial working memory's affordances. If syntax is required, meaning text is not simply/predictably stated, the dyslexic is forced to attempt verbal working memory with the aid of central executive function. Listening to others read aloud is a direct route to the central executive for dyslexics though repeating sequences or directions in order will still be impaired because they require use of phonological working memory.*

General word perception/reading theory

Single word processing is resistant to the effects of intraword spacing as assessed by comparing each subjects' performance to their unlimited capacity, independent, and parallel model via the assessment function and the word capacity analyses. Increased intraword spacing increased RT for both groups which is consistent with Grainger et al., (2003), Vinckier et al., (2011) and Dehanae et al., (2005); relative spacing above two interferes with visual processing of n-grams/words and support the Local Combinations Decoder (LCD) model. The reduced accuracy across all distractor conditions would also support the use of internal/external verbalization of the word and then a loss of the representation or an inability to quickly parse and determine the phonetic difference in the dyslexic's deficient verbal working memory.

Methodological

The universal theory of the reading process has traditionally been based on Western phonological languages. Studying Western phonological language dyslexics, (especially English which has the least orthographic clarity) provides insight into the consistencies and deviations of the reading process when the language's core structure (innate processing advantages provided by phonology), and the logical structure provided by phonetic information are removed; this relieves the actual universal traits of reading processing for all languages, both phonetic and logographic. The application of verbal language processing (input and output) can be examined in future research. The capacity coefficient for accurate targets was not able to differentiate between dyslexics and controls. The assessment function, which accounts for accuracy rate, accounted for variation in in WAIS IV Symbol Search subtest score for dyslexics only. Additionally, further investigation of the first terminating distractor is potentially viable; how dyslexics answer incorrectly appears to be more informative than how they answer correctly.

Application

Further research is needed to assess the accuracy of distractors via assessment function and the more global working memory deficits in dyslexia. Novel approaches to removing the barriers of cost and inconsistent rater reliability for diagnostic tests will greatly improve the identification rate of dyslexics and hopefully move the education and disability legislation towards a more accurate and reliable diagnostic standard that is based on the neurological evidence at the lowest level of processing rather using test designed for another purpose that are confounded by achievement and intelligence level. While the manipulation here, intraword spacing, will not accomplish this result, it is a step in the correct direction. This research also adds to the body of research including Ratcliff (1993) and Welford (1952) that warns of the need to stop the use of parametric assumptions on response time data.

With this in consideration, to address the gap in content validity of cognitive tests for those suspected or diagnosed with dyslexia, subtests that use phonological working memory should not be used to calculate intelligence scores. For example, the WAIS subtests that use verbal working memory retrieval of a sample set of specific terms, e.g. Vocabulary, or are diagnostic of the disabled populations working memory deficits, e.g. Digit Span, should not be used to calculate intelligence scores for school-age gifted programs (see Appendices G and H). Further investigation will need to examine a semantic manipulation with phonetic and visuospatial manipulations (e.g. house vs. homes vs. humus, sell vs. sale vs. cell, or bleed vs. blood vs. blued) to determine if dyslexics use the phonic representation prior to semantic representation, as suggested in the dyslexic reading model in Figure 19.

Construct validity of the DSM-IV definitions of Dyslexia/SLD (American Psychiatric Association, 2013) is built upon convergent validity (correlation to items that it should be related to) and discriminant validity (lack of correlation with items that it should not be related to). When a construct has decades of poor identification and within population incongruence with the available criterion in a variety of combinations, the construct needs to be redefined. Defining a construct by the available measures has left a considerable portion of unexplained variance, as well as variance left unmeasured. Considering the large quantity of unexplained variation within dyslexics as a group negates the assumption that we have an adequate a priori criterion of dyslexia. If researchers and practicians continue to revalidate new diagnostics based on the old concepts of dyslexia and ignore the neurological research on dyslexia, progress in identification and intervention will be stunted. "The criterion model does not provide a good basis, for validating the criterion. Even if some second criterion can be identified as a basis for validating the initial criterion, we clearly face either infinite regress or circularity in comparing the test to criterion A, and criterion A to criterion B, etc." (Kane, 2000, p. 4). The need to find novel approaches to better define the construct validity of dyslexia without the circular logic remains elusive. The newest approach, the Dyslexia Index falls prey to the same errors. For example, the Dyslexia Index manual states "Grades 2-12+ correctly classify 95% of students with dyslexia and 68% of controls" (Breaux, 2018). The Dyslexia Index manual states that using the criterion of less than 90 will correctly identify 19 out of 20 dyslexics, Sensitivity = 0.95, and 13.6 out of 20 controls, Specificity=0.68, for grades 2-12+. Twenty-five percent of dyslexics were within the standard error of the criterion and twenty percent of controls were within in the standard error criterion of which indicates that the subjects in this study had a higher likelihood of correct identification of controls but also higher likelihood of incorrect rejections of dyslexics. This suggests the possible bias against post-secondary higher-functioning adults (the manual states that there will be future research on adult populations). The diagnostic tests continue to measure behaviors that are contaminated by confounds, like education and intelligence, rather than using the neurological evidence at the lowest level of processing.

Limitations

Due to the lack of experimental controls and changes to the methods without the needed changes to the hypotheses, there is not strong enough evidence for or against the suggested theoretical model of dyslexic reading. For the configural processing of words, intraword spacing was adequate to disrupt WSE in this experiment likely due to the increased stimulus display window, and further attempts to disrupt WSE must be attempted to test the proposed theoretical model. Overall, subjects of both groups were less efficient with normal word reading than in prior research using the word capacity coefficient (Houpt, 2012; 2015) highlighting the importance of environmental controls when replicating WSE research.

In order to properly investigate the distractors, a more difficult task (faster response window) would be needed to produce more incorrect responses per capita and assume single target self-terminating within the assessment function. As the major finding in the research is the difference in accurate rate by group, especially with distractors, this analysis would specifically address the workload processing for those trials. The stimulus window for the target/distractor overlapped with the response window in this version which left the target/distractor visible for 900 ms if the subject did not respond as instructed. Covid-19 protocols changed a key control of the study, subject environment. While the lack of environmental experimental controls does lend the results to that of an applied setting, the incongruency with the prior research isolates any findings or the lack thereof.

Likely due to the lack of experimental controls and a longer stimulus presentation and response period, we were not able to replicate the findings on the effects of intraword spacing in controls found in Houpt and Zhang (in press). We can say that in a noisy non-laboratory setting, intraword spacing does not strongly affect the configural processing of words across our experimental groups for RT, though accuracy was affected. Our conversion of Covid-19 protocols also prevented us from completing our hypotheses as planned. While the teleological argument that resilience to the lack of lab quality controls is necessary for the overall goal, the lack of experimental controls makes this study stand apart from the other research in this paradigm. A valid future research question is if our results would be repeated if we had the typical experimental controls.

Future research

Nonlanguage-related deficits in dyslexia

Since the group effect on accuracy was likely due to a deficit of central executive processing of new correspondences, further examination of the perceptual working memory deficits in dyslexia is warranted. Dyslexia causes issues with rapid perceptual processing, including auditory processing, rhythm repetition, tactile tempo-discrimination, audio-visual temporal integration, motion perception, and sequencing in vision, auditory, and tactual stimuli (Bruno & Maguire, 1993; Flaggacco, 2014; Franceschini, 2018; Gori et al., 2016; Huss, Verney, Fosker, et al., 2011; Grant, Zangaladze, Thiagarajah, et al., 1999; Goswami, 2010; Kronschnabel, Brem, Maurer, & Brandeis, 2014; Ramus, 2004, 2012; Tallah, 1998; Yehudah, 2003). Dyslexics have reduced sensitivity to rapid, low intensity visual stimulus and normal sensitivity to high contrast/slow frequency stimulus associated with reduced activation and cellular density of the magnocellular pathway (Livingston, Rosen, Drislane, & Galabura, 1991). Dyslexics have an increased minimum threshold for the detection of movement and reduced activation in V1 and MT of the visual cortex when compared to controls (Eden, van Meter, Rumsey, et al., 1996; Demb et al., 1997, Demb, Boynton, & Heeger 1998). Temporal deficits have explained variance in spelling and reading tasks (Thomson & Goswami, 2008) and sensitivity for variations in temporal patterns predicts phonological awareness (Huss, Verney, Fosker, et al., 2010) with clear impairment in dyslexics.

The broader temporal deficit theories (Goswami et al., 2011; Livingston et al., 1991; Stein, 2001; Tallah et al., 1996; Vidyasagar, 2010) have a neurological basis and measurable behavioral outcomes and also encompass the narrower, but more popular, phonetic deficit theory (Shaywitz, 2005) because phonetic discrimination is a very rapid temporal processing of auditory stimuli. Future research in the word superiority effect and dyslexia should include non-phonetic temporal discrimination and sequencing tasks in order to investigate its explanatory contribution when comparing within subject processing. Comparisons of verbal working memory should also be expanded, and verbal working memory cognitive subtests should be excluded from intelligent score compositions if used for diagnosis or selection. It is also important to emphasize that categorical group modeling (dyslexics verse controls) is problematic due to the uncertainty in current diagnostic methods, lack of unified definition/criteria, and the large proportion of undiagnosed dyslexic contaminating controls (European Dyslexia Institute, 2018).

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Appendix A: Phonetic and Logographic Language as a proxy for Dyslexia

The dyslexia model was built by comparing the following neurological evidence to Perfetti's and Coltheart Models. According to configural processing research, familiar single-word reading is holistic due to visual expertise; this is akin to the concept that single-word reading of a familiar word is logographic, meaning the symbols to lexicon process is only through visual correspondence and do not hold phonetic information, due to visual expertise (Diamond & Carey, 1986; Tanaka & Sangco, 1997). The notion that word perception is learned expertise in visual recognition is supported by neurological theories, specifically the bigram coding hypothesis (Vinckier, Qiao, Pallier, et al., 2011) and the local combination detector (LCD) model (Dehaene, Cohen, Sigman, & Vinckier, 2005). Repeated exposure of the visual form and sound profile changes the FFA (neuronal migration hypothesis) to specialized for reading language. As phonetic processing, speech/articulation, and auditory language processing is left-lateralized and consistent with neuronal plasticity and the migration hypothesis, efforts to conserve resources and consolidate areas regularly used in parallel or in automated series, as expertise is established, the left FFA is converted to the Visual Word Form Area (Dehaene & Cohen, 2011). When there is a neurological phonological deficit (dyslexia), left lateralization is reduced and the connectivity associated with acquisition reading/language is altered (Guidi, Velayos-Baeza, Martinez-Garay, et al, 2018; Finn, et al, 2015). And through the proposed dyslexic reading model, the difference in the neurological development are consistent with their accommodated acquisition strategy

Phonetic and logographic languages

Phonetic written language is less burdensome to acquire and decode than pictographic and logographic language. The difficulty of learning and using pictographic and logographic languages has led to the extinction of pictographic and the non-primary use of all remaining logographic languages (Gelb, 1952; Zhu, 1987). From an ecological viewpoint, there are greater restrictions in the construction (lingual dexterity) and identification (auditory perception) of spoken language than of the restrictions of construction (finger dexterity) and identification (visual perception) of written language. Typically, phonetic written language corresponds closely with the spoken language (one to one grapheme to phoneme correspondence) (Sproat & Gutkin, 2021). Logographic written languages traditionally do not primarily rely on grapheme-to-phoneme correspondence, but rather orthography to semantics. The only modern logographic language, Kanji, has tonal and phonetic correspondence (syllabic and phoneme) for the phonetic components and inconsistent correspondence of phonetic/tonal to semantics for the logographic components pushing he logogram to semantic processing (Cao, Lee, Shu, et al., 2010; Ho & Bryant, 1997; Ho & Bryant, 1999; Ho, Chung, Lee, Tsang, 2007). Due to the inconstancies, there is increased visual symbol complexity in order to differentiate each syllable or word (Hua & Perfetti, 2003; Ho & Bryant, 1997; Ho & Bryant, 1999; Sproat & Gutkin, 2021). The consistency of the symbol to phoneme correspondence, i.e. clear orthography, in phonetic languages corresponds to plasticity in left hemisphere orientation of the Visual Word Form Area (VWFA) to be prominent to the more temporally sensitive left PT to distinguish phonemes. The visuo-spatial correspondence with syllabic and phonetic correspondence in logographic languages led to bilateral visual word area of the FFA with connectivity to both visual spatial and phonetic processing centers (Cao, Peng, Liu, et al., 2009). Logographic reading is a plausible compensation for the literate dyslexic without phonetic training; Without the ability to identify, blend, or decompose phonemes, word recognition is paring of a visual symbol to a meaning and/or to a phonetic pattern. The neurological evidence suggests bilateral activation of FFA similar to visual symbols rather than localized to left and the lack of typical white matter pathways between the FFA/VWFA and left occipital temporal cortex.

Phonetic languages and associated neurological processing

In phonetic languages, VWFA and posterior superior temporal sulcus activation provides automatic phonological -orthographic conversion, followed by left posterior middle temporal gyrus staging for consolidation, and subsequent semantic processing by the anterior middle temporal gyrus (MTG) with functional connectivity with the default mode network and inferior prefrontal cortex yielding comprehension and inference (Carreiras, 2009; Chen, 2019; Davey, 2016; Nakamura, Dehanae, Jobert, et al., 2005; Perfetti, 1999; Richlan, Kronbichler, & Wimmer, 2009; Barbeau, Descoteaux, & Petrides, 2020; Snowling, 2005). According to Dehaene's Neuronal Migration Hypothesis, the associative pairing of letters/words and phonemes/spoken language left temporal cortex) causes a neuronal migration where the left FFA tunes to the specific categorical stimuli. This stimulus is identified as a component of language and through associative learning is functionally connected to the prior auditory and spoken language networks. As acquisition occurs, the gain of high lexical quality and stability can be established as relatively high activation (high lexical quality) and specificity (stability) in the left FFA, now the visual word form area, (Dehanae et al., 2010; Manzavio et al., 2012). The articulus facsucus/inferior longitudinal facsicatis volume of white matter pathways between the VWFA and the left temporal lobe is predictive of behavioral reading measures. The arcuate facsucus/inferior longitudinal facsicatis between the VWFA and the posterior superior temporal sulcus processes the phonological to orthographic mapping to prepare for written word semantic retrieval (Chen, 2019; Dehanae 2020 pre-release) which a white matter tract known to be reduced in dyslexics from infancy (Langer, Peysakhovich, Zuh, et al., 2017) and behaviorally targeted in this research. Finally, the left superior middle temporal gyrus facilitated the processing of semantic matching by the remaining anterior MTG, posterior MTG, and medial MTG (Xu, 2019).

As the pairing stabilizes with repeated exposure, the process becomes automatic (Chen et al., 2019; Jitsuishi, Hirono, Yamamoto, et al., 2020) and requires attentional control is (de Schotten, 2014; Vidyasagar, 2019)). Perrone-Bertolotti (2014) grapho-phonemic conversion emphasizes that the visual stimulus to phonetic association is top-down as well as bottom up. While the bottom-up influence of the VWFA is clear, the top-down influence drives more complex differentiation and identification of written language. The functional connectivity of the fronto-parietal attention network nodes (top-down influence) can predict behavioral scores in reading, though reading scores cannot predict scores of behavioral attentional measures (Chen, 2019). Sharoh, van Mourik, Bains, et al. (2019) found that top-down modulation from the left middle temporal gyrus assists in the identification if orthographic compliance is unclear as well as contribute to controlled semantic retrieval (Davey, Thompson, Hallam, et al., 2016). Native language orthographic clarity also contributes to neurological compensatory mechanisms (Martin, Kronbichler, & Richlan, 2016), acquisition of reading skills (Landerl, Wimmer, & Frith, 1997), and performance on diagnostic tests (phonetic awareness, rapid naming, and short-term working memory) (Landerl, Ramus, Moll, et al., 2012). Activation of the left inferior frontal gyrus and ventral occipitotemporal cortex was found in typical English language subjects is theorized to represent the shared orthographies reading and spelling tasks (Purcell, Jiang, & Eden, 2017) (which are areas associated with under activation in dyslexics (Finn et al., 2014; Richlan et al., 2009)).

Logographic languages and associated neurological processing

Logographic reading does not follow Perfetti's Reading Process Model (Perfetti et al., 2005; Perfetti, 2006), phonology is a post lexical task in logographic languages (Dylman & Kikutani, 2018). Logographic reading takes visual input as morphemes or morphosyllibic units; Each morpheme/morphosyllibic unit within the logogram has a semantic meaning to use alone or build upon, similar to deriving meaning from uncommon and complex Latin and Greek words (Chen & Kao, 2002; Dylman, 2018; Cole, 2007; Wong, Tong, Lui, et al., 2021). Logographic reading depends on the one to one correspondence of the morpheme and semantics though there are many contrary instances (Sproat & Gutkin, 2021) . The reader can deduce the proper semantic interpretation until automaticity in reading is obtained. In logographic languages, there will be a temporal delay in retrieving phonetic representations (speaking) compared to phonetic language readers; Thus, phonetic retrieval is identified *after* the semantic meaning, delaying verbalization of a single word (Dyllman, 2018). Logographic comprehension employs a situation model within the central executive using feature salience and spatial relationships rather than linear ordering of phonemes and grammar (Chen & Kao, 2002; Wong, Tong, Lui, et al., 2021; Yang, Zhang, Meng, 2018), that parallels reading in dyslexics of any language. Studies of Chinese logographic reading (Kanji) have shown bilateral activation of the OTC (VWFA/FFA) while reading logograms compared to greater left lateral activation for phonetic words, increased intraparietal functional connectivity, and increased connectivity of the left middle temporal gyrus (anterior and mid as semantic processing and posterior as language processing), and reduced white matter pathways between the left arcuate fasciculus and inferior fronto-occipital fasciculus (Dong, Nakagawa, Okada, et al., 2005; Nakagawa et al., 2005; Su, Zhao, de Schotten et al., 2018; Xu, 2019; Yamaguchi et al., 2002; Zhang et al., 2013; Zhang et al., 2014). The increased activation of the right temporal lobe and right to mid FFA are believed to be associated with visual spatial to orthographic processing (Smith, Jonides, Koeppe, et al., 1995). Logographic written language has greater activations in the ventral pathway while (Tau, Laird, Li, 2005) phonetic had greater activation in the dorsal pathway (Kim, Kim, Kang, et al., 2017) which provides a context for the heavily visuo-spatial sensitive languages to be processed differently than the heavily temporally sensitive auditory processing of phonetic languages.

Appendix B: Limitations of Existing Diagnostic Methods based on the Dyslexia Reading Model

Dyslexia is a genetic, neurological disorder that alters neurodevelopment in utero resulting in consistent cortical ectopias and dysplasias in the area typically associated with the language/reading circuit left perisylvian region, deviations from typical development in the fusiform gyrus/visual word form area, left and right PT volume, atypical bilateral functional connectivity of the phonemic/language "reading circuit", and reduced gray matter volume in the dorsal parietal cortex (Finn, 2014; Galaburda & Kemper, 1979; Galaburda, Sherman, Rosen, Aboitiz, & Geschwind, 1985; Geschwind & Galaburda, 1985; Kubuto, Joo, Huber, et al., 2019; Mascheretti, de Luca, Trezzi, et al., 2017; Ozernov-Palchik & Gaab, 2016; Peterson & Pennington, 2012; Yu, 2018).

Diagnostic tools for dyslexia capture a prohibitive amount of construct irrelevant variance. By deconstructing the reading processes to the lowest concrete behavioral and neurological correlate, we hope to capture the first deviation in the reading process of literate dyslexics and capitalize on their error to more accurately and reliably identify dyslexics with a fraction of the resources.

Dyslexia is a genetic, neurological disorder resulting in atypical development of the language circuits (Peterson et al., 2015; Richlan, Kronbichler, & Wimmer, 2009; Richlan, 2019; Shaywitz, 2006; Siegler, 2006; Snowling, 2005) and the lack of typical automaticity and synchronicity in cross-perceptual and executive functions (Casini, Pech-Georgel, & Ziegler, 2018; Finn, Shen, Holahan, et al., 2014; Kronschnabel, Brem, Maurer, et al., 2014; Pekkola, Laasonen, Ojanen, 2005; Tallal, 1984). This prohibits the associative learning required for typical language acquisition (Clark, Helland, Specht, et al., 2014; Park & Lombardino, 2012; Raschle, Chang, & Gaab, 2011). Between 5% to 12% of the population has dyslexia (Moody, 2004; Peterson et al., 2015; Shaywitz, 2006; Siegler, 2006; Snowling, 2005). Despite being recognized as a disability under the American Disability Act in 2007, there are still multiple diagnostic criteria, i.e. a variety of psychometric test protocols, with low stability over time and significantly low agreement among the methods (Breaux, 2019; Brown-Waesche, 2011; Ferrer, 2009; Reynolds, 2009; Siegel, 1989; Wagner, 2019). These basic psychometric deficiencies have resulted in a low identification rate (National Center for Education Statistics, 2017) and error variance confounding research in multiple domains. Progress in understanding and remediating the negative consequences of the disorder requires further conceptual development of the construct and more reliable, cost-effective methods of diagnosis.

The overarching limitation of the existing methods of diagnosis of dyslexia as a phonetic deficit, is their lack of specificity to low level word recognition processes, which we have shown differs between the dyslexic and non-dyslexic population, and which is unique to reading as opposed to language comprehension. The use of cognitive and achievement tests to diagnose dyslexia neglects the root deficits and emphasizes the output patterns which, due to variability in general intelligence level, past intervention, and educational attainment, cannot validly or reliably be used to identify dyslexics (Stanovich, 2005; Wagner, 2019) In the U.S., there are three definitions available for the identification of dyslexia, aptitude-achievement discrepancy, low achievement without other explanation, and response to intervention (RTI). The Pearson's Dyslexia Index is an aptitude-achievement discrepancy (despite the deficits in dyslexia being unrelated to intelligence level (Tanaka, et al., 2011)), where standardized psychometric tests are given and a discrepancy greater than the allowable normed population, 1.5 SD, in typically (there is no required standardization currently) reading, phonetic awareness, comprehension and Functional Intelligence. The DSM-V promotes the more general impairment of phonemic discrimination and below average reading ability without alternative explanations (American Psychiatric Association, 2013). The procedures outlined in the Individuals with Disabilities Education Improvement Act of 2004 are referred to as the response to intervention (RTI), i.e. scaled typical educational invention over time until the only remaining cause is a disability. The three definitions do not correlate well. ERP readings (frontal/parietal) of 36 hours old infants listening to their mother talking successfully predicted 76.5% of the children diagnosed with dyslexia at age 8 (Molfese, 2000), yet Wagner et al (2019) found that the agreement between aptitude-achievement and response to intervention (RTI) identification methods was only 31% and aptitude-achievement to low achievement is 32%. These results point to construct underrepresentation and construct irrelevant variance. Cut offs scores for classification/identification are used, possibly inflate the rates of false positives in the non-dyslexic/typical population and false negatives in the dyslexic/non-typical population. Also problematic is that intelligence quotient criterions, e.g. the tests that make up the cognitive/IQ tests, are largely language based, i.e. the language scores typically explain the majority of the variance within the full-scale score (Rowe et al., 2010) (Additional information on adverse impact in cognitive test in dyslexics and other special populations can be found in Appendix G and H).

Appendix C: COVID-Protocol Adaptions

The experiment was adapted for online collection given the Covid 19 pandemic. The major adaptions are as follows:

1. Experimental controls typically found in perceptual research were sacrificed to avoid delay. Data collection was 100% online and the environment, distractions, and even visual angle varied by participant.
2. A variety of changes were made to several of the psychometric tests for delivery over WebEx. Modifications were made to the selection psychometric subtests (see Replacement of WASI Coding) to those that were the most compatible with online conference delivery. Nonetheless, several tests like Symbol Search and Spelling response delivery were so drastically altered, subtest standardization and composite scores cannot be validly compared to the populations who take the tests using the documented protocols. And again, a valid future research question is if our results would be repeated if we had the typical test delivery and response protocols.

   Replacement of WASI Coding.

   Coding skill hypotheses were not tested due to Covid protocols, though the tests that are highly correlated with WASI Digit Span ($r = .42$), Arithmetic ($r=.43$) and Symbol Search ($r=.64$) using subjects average age range 20:0-24:11 Table A.3 p. 140 Intercorrelations of Subtest, Process, and Composite Scores). Since Coding could not be given, we examined Digit Span and Symbol Search. In our model for Dyslexia reading and phonetic retrieval, there is a lack of automaticity in retrieval of phonic information and the concept. This makes Rapid Picture Naming a coding task that is sensitive to temporal processing (timed) that requires phonic recall of specific words.

Appendix D: List of Word Stimulus

STEM	Letter_variant_1	Letter_variant_2	Letter_variant_3	Letter_variant_4
come	csh	oa	mdrpnv	eab
then	tw	he	eai	ynme
said	splmr	ak	in	dl
feel	fhpr	eu	el	ltds
must	jmbdlr	uoi	st	th
care	cdrbfmhw	auo	rmskgvpfn	edst
came	cnsgldft	oa	mrskgvpfn	ep
mind	fkmwbh	ie	nl	detik
show	sc	hln	oa	wtpeo
hold	thcsgbfm	oe	lo	dye
hard	hcyw	ae	rn	dmpe
lost	lmcph	aoiu	sof	tes
part	pcft	ao	rsc	tk
hand	hlbsw	ai	rn	dg
deal	rdmshv	ei	al	ldrfn
word	wlcf	oa	ro	kdenm
wish	wfd	ia	ts	he
read	rhdl	eo	ae	ldrp
line	lfmnwpdv	iao	kfnvmc	ek
send	sbtlm	ea	ne	dt
fire	fhwtsd	iao	nvrl	em
past	lpfecv	aoe	src	ts
beat	bshmn	eor	saln	trmnku
pass	pmbl	au	syldwn	ts
born	bhtwcp	oua	ro	ne
lead	hdrl	eo	an	dnkpf
seat	sbhmn	etw	na	tls
fell	wtfscbyd	euai	le	lt
land	hlbsw	ae	ni	de
ball	cfwbhtmg	aieu	li	lde
crap	ctw	rhl	ao	pb
cost	mlcph	oa	sal	ty
park	pdmb	ao	rc	tk
wind	fkmwbh	ia	nl	desgk
cops	copt	oua	pwn	sye
dare	cdrbfmhw	ai	rtml	ekn
tree	tf	rh	ue	eky

shop	sc	th	oi	pwteo
pack	bpjlsrht	aieu	cr	ket
bank	btrys	au	cnr	kdg
hall	chfwbtmg	aiu	liu	lft
form	fwdn	oia	ra	mtkde
bear	hydbwnftgr	eo	ae	rtmnku
tape	tc	ay	kplm	es
boat	bcg	eor	auol	tr
coat	cbg	oh	sal	tl
lift	lg	ieo	fs	et
blew	bf	lr	oe	wd
suck	sldbtyp	uiao	cn	hk
ship	scw	hlkn	oi	pn
race	frplm	ai	ctrgvk	ek
loss	lbtm	oea	stg	tes
tall	tcfwbhmg	eaio	li	lke
band	hlbsw	aeoi	nl	dkg
male	mstpdgb	aiuo	kdltrzc	el
load	rlt	oe	aru	dnf
slip	sfc	hlkn	ia	pmt
rise	rw	io	dscp	ek
post	mlpch	oae	sre	te
bath	bpmoh	oa	ts	hs
dies	dltp	oiu	egb	sdtm
bust	jmbdlr	ue	st	tyh
sale	smtpdgb	ao	mvfkln	et
wore	wmstbcf	eoia	rk	ekdnm
belt	bfm	eo	slan	tl
rose	lnrhpd	oi	spldb	ey
pink	pslwfmr	iu	cn	kestg
thin	tcs	hw	iea	sn
cast	lcfpev	ao	sr	teh
mile	mfpvt	iauo	nlc	ekdl
hunt	har	ui	rn	tgk
duck	lsdbtyp	ueo	cn	kt
role	rhpsm	ou	lspdb	le
mate	mlhdrgf	au	kdtlrzc	eht
sink	splwfmr	iua	cnl	kgs
tone	dgnbtzlc	ou	nr	esg

cure	scpl	uao	rtb	eblt
mass	mpbl	iaeo	srp	skh
sand	shlbw	ae	in	dgek
sons	stc	oi	nb	gs
golf	gw	ou	lo	df
sore	smwtbcf	oui	mrl	et
tune	tj	ou	nb	ea
pile	fmpvt	ioa	lpnk	el
bail	bjmftnshr	ao	li	lt
lane	lsc	aio	tnkmc	ed
math	bpmoh	ayo	ts	het
bond	bfp	aoei	nl	deg
chip	scw	hl	ioa	pnc
lend	slbtm	ea	na	dst
slap	scf	lnow	ia	pmy
cuts	cnpg	ua	tpb	es
torn	tbhwcp	uo	rw	ne
chop	sc	hro	oia	pw
rice	nrvdml	ia	cdsp	ehk
lame	ncslgdft	ai	mtknc	epba
tale	tmspdgb	ai	klpm	ekl
sits	hsfbwp	ie	tnr	se
mall	cfwbhtmg	ai	li	le
fort	sfp	oa	ro	tmkde
ward	hwcy	ao	rn	dmnspe
lick	plsknrthw	iuoa	cn	ke
pole	hrpsm	oia	lspk	eol
chew	cwp	rh	eo	wf
tons	tsc	oe	nseyp	esg
port	psf	ao	rse	tkn
tore	mwtsbcf	oiy	rn	en
ties	ltdp	io	ep	sd
bare	cdbrfmhw	ao	rsbkl	esnkb
bore	mbwstcf	oa	rn	en
pale	pmstdgb	aio	glc	ems
dame	ncsgdlft	ai	mtrl	ep
sins	swp	io	ntr	gsk
cart	cpft	au	rs	etds
rank	btrys	ai	nc	kg

bold	thcsgbfm	oa	ln	dt
rack	brjplsht	aoi	cn	ke
cans	cfp	ao	rtnpb	se
core	cmwstbf	oau	mrdpnv	endk
seed	nsfwdrp	ehul	en	dnmsk
bets	glsbpj	eia	tde	sa
deed	ndfwsrp	ei	ea	dpr
cord	wclf	oa	rl	dnek
fare	cfdrbmhw	aio	rcktmd	emt
pope	hnrpdc	oi	plsk	es
slam	sc	lcw	ai	pmy
sole	shrpm	oa	mlr	edo
bunk	bpjhsdf	au	nc	ks
bolt	bc	oe	aluo	td
rick	pskrnlthw	ioa	csn	khe
cape	ct	ao	rmspkgvfn	es
bass	pbml	ao	sgrt	seh
chow	sc	hr	oe	wp
mild	mw	io	nl	dkel
hunk	hpjbsdf	uo	nl	gtk
slot	sp	hlpn	oi	twb
fart	pfct	ao	rcs	tme
herd	hn	ea	ral	edosb
sunk	spjbhdf	uia	cn	kg
crop	dcp	rho	oa	pw
lone	ldgnbtzc	oia	nvs	ge
pins	pws	iea	nget	ksetg
dine	fdmlnwpv	io	nmvcr	eg
cane	cls	ao	rmskgnvpf	es
mole	mhrps	oaiu	rvld	ed
mold	thcsgmbf	oi	lo	de
clap	csf	rlh	ai	pymwn
toll	trdp	eoia	lo	ld
bats	bcerho	aie	tgrs	hs
cope	chnrdp	oa	mpdrnv	esy
mash	cwmrdhb	au	st	hsk
bind	fkmwbh	iaeo	nr	dg
dork	wdfpc	oa	rc	kmy
prop	dpc	ro	oe	pms

lace	flrpm	ai	ctknm	ek
coop	clph	ohr	ou	lkp
crow	gc	rh	oe	wp
mutt	mb	ua	st	te
lime	ltd	ia	kmfvnc	eobp
bash	cwbrdmh	au	st	hes
mist	mlf	uoi	sn	ts
caps	cmlt	oau	prtnb	se
cone	cdgnbtzl	oa	mndrpv	es
pits	phfsbw	uieo	tgne	sy
grad	gb	lr	ai	dbym
rust	jmrbdl	ue	sn	th
sire	sfhwtd	uio	rdzt	es
mute	cm	ua	tl	et
sank	btsry	aiu	nc	kdge
dire	fdhwts	ia	rmvcn	et
mush	mprbh	ua	cs	ht
puss	pf	au	st	sh
mare	mcdrbfhw	aoe	krdltzc	eks
colt	cb	ou	lsa	dta
honk	hm	ou	onc	kg
taps	tmcl	aio	pgb	es
poll	prdt	uoi	lo	leo
hare	hcdrbfmw	aei	vrt	edmp
moss	mblt	oiea	sm	ts
tile	tfmpv	ia	mlrd	elt
mink	mpslwfr	io	nl	dekti
runt	rah	ue	ns	st
wand	whlbs	ai	nr	td
tack	btjplsrh	aui	clns	ko
lass	lpmb	aeo	swdybp	ts
cons	cst	oa	pnw	se
trey	tgp	hr	ea	yek
lice	lnvrdm	ia	kfcvnm	ek
cubs	cs	ua	tpb	se
rink	rpslwfm	ia	nsc	gk
dell	wtdsfcby	eou	la	li
curt	hc	ua	rl	tebl
ware	wcdrbfmh	eaoi	rkvgd	emndsp

Appendix E: Dyslexia Background Questionnaire

Have you received reading tutoring or interventions? When? How long?

Did you receive specific phonetic (letter to sound(trainings/tutoring?

Did you receive speech interventions in elementary school?

Do you regularly leaving out articles, propositions, and pronouns when writing first drafts of papers, emails, and text messages?

Do you regularly putting words and phrases out of order (not following typical orthography/grammar structures) when writing first drafts of papers, emails, and text messages?

Appendix F: Adverse impact in cognitive tests for dyslexics and other special populations

In terms of adverse impact on disabled populations known to have no effect on intelligence, i.e., Dyslexia/SLD, Dyscalculia/SLD, ADHD, and high functioning Autism, cognitive subtest that are known to have a medium to large Standard Difference. According to Pearson's WAIS IV, "the *Standard Difference is the difference of the two test means divided by the square root of the pooled variance, computed using Cohen (1996) Formula 10.4*" (WAIS Technical Manual, p.108, 109, 110, and 115). We put forth that subtests, indexes/composites with medium to large Standard Difference should not be used when calculating IQ, especially for gifted programming selection. Cohen (1996) Formula 10.4 (Pearson's "Standard Difference"):

$$g = \frac{\overline{X}_1 - \overline{X}_2}{s_p}$$

The "standard difference" (Cohen refers to Formula 10.4 as "Gamma") is the difference between the two groups means over the square root of the pooled variance (s_p). For interpretation, Cohen writes, "*...you can use the guidelines established by Cohen (1988), in which .2, .5, and .8 represent small, medium, and large effect size.*" (Cohen, 1996, p. 303). Cohen clarifies that adequate prior research was completed to produce the standard difference which we assume was carefully undertaken by Pearson and as documented in previous test versions.

For Dyslexics/ Reading Disabled/SLD the cognitive subtests within the WAIS-IV which has a medium to large standard difference are Digit Span (.66; Digit Span Forward (.84), Digit Span Backwards (.64)), Vocabulary (.78), Arithmetic (.97), Coding (.56), Letter-Number Sequencing (1.03), and Figure Weights (.58). For the indexes/ composite scores with medium to large standard difference/Gamma, Verbal Comprehension Index (.61), Working Memory Index (.90), and the overall Full Score IQ (.71).

In the Standards for Educational and Psychological Testing, Section 13.01 states "It is the responsibility of those who mandate the use of tests to monitor their impact and to identify and to minimize potential negative consequences. Consequences resulting from the uses of the test, both intended and unintended, should also be examined by the test users." Using cognitive subtests to composite indexes that are known by the test manufacturers have medium to large effect size differences (standard difference/Gamma)in protected populations to determine gifted program entry is unethical and likely illegal, considering there are subtests and indexes available with less adverse impact. These issues are also found in the child version of cognitive tests. A comprehensive evaluation of all tests, indexes, and composites used to quantity intelligence in the pre-kindergarten -12 grade student population should be required if these tests are used for gifted program selection so the least bias combination of subtests are used, and the proper error is assigned given that individual student is from a non-normed subpopulation. Based off the in WAIS IV subtests with the least adverse impact were selected for this research.

Lastly, the current definition and diagnostic methodology's variance cannot reliably explain the patterns of neurological connectivity/activation or location/size/density of neuronal tissue or even reliably capture the behavioral/cognitive/genetic phenotypes associated with dyslexia (Bloom, 2010; Galaburda, 2006; Gialluisi 2019; Guidi, Velayos-Baeza, Martinez-Garay, et al., 2018; Keri, 2016; Mascheretti, et al.,, 2016 Shaywitz, 2004; Shaywitz & Shaywitz, 2008; Stanovich & Segal, 1994; Welcome, Leonard, & Chiarello, 2010). In conclusion, the use of cognitive and achievement tests to diagnose dyslexia neglects the root/core deficits in dyslexia and emphasized the output patterns which, due to variability in general intelligence level, past intervention, and educational attainment, cannot validly or reliably be used to identify dyslexics. In other words, while aptitude-achievement discrepancy analysis, low achievement, and

Response to Intervention (RTI) methods can be used to diagnosis dyslexics, not all dyslexics can be identified using aptitude-achievement discrepancy analysis, low achievement, and Response to Intervention methods.

Appendix G: Nonstandard intelligence score for research use only due to adverse impact in Reading Disabled subpopulation

The following factors lead us to a modified GAI calculation method, referred to herein as estimated General Intelligence Score for subpopulations excluded from normative sample (eGIS). The term "bias" and "adverse impact" are operationalized herein as a significant reduction of score ($p<0.05$) due to subgroup membership.

1. Those with "Learning Disorders" are excluded from the normative sample for the WAIS IV (WIAS IV Technical and Interpretive Manual, 2008, p. 31 Table 3.1);
2. There is evidence by the test manufacture and/or third-party research that there is adverse impact in the subtests, composite score (VCI and WMI), and Full Score IQ (see Mean Performance of Reading Disorder and Matched Controls, WIAS IV Technical and Interpretive Manual, 2008, p. 108 Table 5.24);
3. The alternative intelligence score, GAI, offered by the test manufacturer does not address the adverse impact in the subtests required to calculate the alternative intelligence score, i.e. bias subtests required to be included in GAI calculation (WIAS IV Technical and Interpretive Manual, 2008, p. 168-171, Appendix C;
4. And, as the bias subtests in question, Vocabulary and Information, have high intercorrelation with Similarities in normed population across age groups , .78 to .62 respectfully (WIAS IV Technical and Interpretive Manual, 2008, p. 138- 150, Appendix B).

Calculation of eGIS :

1. Estimated Vocabulary/Information score from Similarities scaled score using the age appropriate table in Table A.1 in the Administration and Scoring Manual (2008) (i.e. used SI scaled score for missing scores)

2. Calculates VCI with matched scores using prorated method from Table A.8 in the Administration and Scoring Manual (2008) (decimals rounded down)
3. Calculate GAI at 90% CI (Table C.1 in the Administration and Scoring Manual (2008)
4. Comparing the eGIS to GAI is not psychometrically valid. eGIS is used in this research to compare our experimental groups only; Extrapolation of the scores to the general population is not valid.

*Note: Covid-Safe Protocols prevented out use of Block Design so it's scaled score is estimated using the mean of the scaled Matrix Reasoning and Visual Puzzles (decimals rounded down)

Appendix H: "Cohen (1996) Formula 10.4" use to select cognitive subtests

Due to the Covid protocols during the data collection period, the WIAS IV and WIAT III were taken over teleconference with stimuli projected over webcam. Due to the Covid-safe protocol adaptions of typical procedures, e.g. size of stimuli, interaction with stimuli (i.e. writing on screen rather than stimuli booklet and pencil), and occasional audio/visual delays/misperceptions, we are not able to report GAI (General Intelligence Index) or FSIQ (Full Score Intelligence Quotient). Since we are doing a simple comparison, we limited the WAIS subtests to Similarities, Digit Span, Matrix Reasoning, Symbol Search, and Visual Puzzles. Our selection was based on several factors, including required deviation from typical testing protocols, 'face validity issues with' adverse impact on those with reading disability based upon the genetic and developmental neurological deviations and known phonetic and verbal working memory deficits, and factor loadings on "g" in previous research on dyslexics. Our goal with the cognitive subtests is to compare the experimental populations levels of "g" in the most unbiased test possible with the Covid protocol restrictions.

Cohen (1996) reports formula 10.4 effect sizes should be interpreted as 0.2 as small, 0.5 as medium, and 0.8 as large.

According to Pearson (2008) Full Score Intelligence Quotient (FSIQ) means for reading disabled ($M=88.7$, $SD = 11.7$) versus the controls ($M=97.9$, $SD = 14.0$) with a difference of 9.18, $t(34) = 3.18$, $p<0.01$. $d= .71$ (WIAS IV Technical and Interpretive Manual, 2008 p. 108; Funder and Ozer, 2019). Mean difference (Cohen's g) was not reported for GAI despite being the suggested intelligence score for reading disabled population.

According to Pearson (2008), Working Memory Intelligence (Scaled Score Composite) has the greatest difference in means for reading disabled adults versus the control population, reading disabled (M=88.9, SD=9.4), control (M=101.1, SD= 16.8) with a difference of 12.21 ($t(34) = 3.64$, $p<0.01$, $g = .90$ (large effect size)) (WIAS IV Technical and Interpretive Manual, 2008 p. 108). The adverse impact on the reading disabled can be interpreted as reading disability has a large effect on the scaled score composite for Working Memory Intelligence (Cohen, 1988). For almost forty years, (Baddeley, 1988; Alt, Fox, Levy, Hogan, Cowan, & Gray, 2021) researcher have theorized that the common deficits in dyslexia to be related to the perception and processing of phonological information and a phonological loop/articular rehearsal deficit. Digit Span contains three tests; Forward which "involves rote learning and memory, attention, encoding (verbal working memory), and auditory processing", "Backwards "involves (verbal) working memory, transformation of information, mental manipulation, and visual spatial imaging," and Sequencing involves " (verbal) working memory and mental manipulation (WIAS IV Technical and Interpretive Manual, 2008, p. 15). Unfortunately, the other subtests in the WAIS -IV are more bias against those with a reading disorder. WIAS IV Technical and Interpretive Manual (2008), reported a Digit Span subtest score difference in reading disorder (M= 8.5, SD = 2.2) and matched controls (M= 10.4, SD = 3.2) with a difference of 1.82 ($t(34) = 2.7$, $p = 0.01$, $g = .66$). The other two tests that can be use in WMI composition score have more bias for reading disabled than Digit Span. Letter-Number Sequencing is similar to Digit Span but includes letters, (reading disabled (M= 8.4, SD = 1.5) controls (M=11.1, SD= 3.4) mean difference 2.68 ($t(34) = 3.92$ $p < 0.01$, $g= 1.03$ (very large effect)); and, Arithmetic where the subjects must properly encode and transcribe verbal and visual information (reading disabled (M= 7.5, SD= 1.7) controls (M= 10.1, SD= 3.4) mean difference 2.59 ($t(34) = 4.17$, $p<0.01$, $g = .97$ (very large effect)). Arithmetic large effect can be non-intuitive, note Kurdek and Sinclair (2001) found unique variance for kindergarten verbal skills for predicting the students' mathematic achievement in 4th grade highlighting the verbal load onto mathematical tests performance when subjects are required to encode and transcribe the information verbally.

The goal of giving a test of Verbal Comprehension Intelligence in this research is to compare the experimental groups so we selected the VCI test that, in the WAIS III had the highest loading on g on the dyslexic population (Laasoneen, Leppamaki, Tani, and Hokkanen, 2009) and allows for compensation for low exposure/ability in typical population by a slight loading to PRI (Weiss, Keith, Zhu, Chen, 2013) or accommodation for neurological deficits in processing in dyslexics. WIAS IV Technical and Interpretive Manual (2008), reported a Similarities subtest score difference in reading disorder (M= 8.6, SD = 2.9) and matched controls (M= 9.8, SD = 3.4) with a difference of 1.24 (t (34)= 1.75, p = 0.09, g = .39. The other two tests that can be use in VCI composition score have more bias for reading disabled than Similarities; Vocabulary (reading disabled (M= 7.5, SD= 2.5) controls (M= 9.9, SD= 3.6) mean difference 2.41 (t (34) = 4.13, p<0.01, g = .78) and Information (reading disabled (M= 8.3, SD = 2.7) controls (M=9.5, SD= 3.0) mean difference 1.21 (t (34) = 2.18, p =.04, g= .43.

According to Pearson (2008) Reading disability has a large effect (Cohen (1996) (d=.48) on Perceptual Reasoning Intelligence Scaled Score Composites (Cohen, 1988; Funder, 2019). The reported difference in means for reading disabled is (M=91.1, SD = 13.8) versus the controls (M=97.3, SD = 11.9) as 6.24, t(34) = 2.13, p=0.04. g= .48 (WIAS IV Technical and Interpretive Manual, 2008 p. 108). Block Design could not be adapted to fit Covid protocols. We selected two of the four remaining tests for PRI that are not supplemental subtests, Matrix Reasoning (reading disabled (M= 8.4, SD= 2.6) controls (M= 9.4, SD= 2.8) mean difference .94 (t (34) = 1.74, p=.09, g = .35) and Visual Puzzles (reading disabled (M= 8.4, SD = 2.8) controls (M=9.7, SD= 2.6) mean difference 1.15 ($t(34) = 1.92$, $p = .06$, $g = .42$), although none of the PRI subtest showed a significant difference in reading disabled and control samples.

Unfortunately, none of the Processing Speed Intelligence Tests could successfully be converted for use with the Covid protocols. Both Coding and Cancellation would require considerable writing on the screen. Symbol Search was more feasible by projecting the worksheet on the subject's screen and allowing them to write using the WebEx annotation tool. Approximately seven subjects (four dyslexics and three controls) of the subjects had technical issues due to OS Chromebook/Chrome browser or lack of technical know-how (IRB did not include requiring the download of the WebEx software). There are also vast speed and accuracy differences in writing with a mouse and writing with a pencil so we cannot standardize these scores. WIAS IV Technical and Interpretive Manual (2008), reported a slight advantage in Symbol Search subtest score difference in those with a reading disorder ($M = 9.9$, $SD = 2.9$) versus matched controls ($M = 9.5$, $SD = 2.4$) with a difference of .34 ($t(34) = 0.54$, $p = 0.6$, $g = .13$). The other two tests that can be use in PSI composition scores were not significant; Coding (reading disabled ($M = 8.2$, $SD = 2.2$) controls ($M = 9.4$, $SD = 3.1$) mean difference 1.18 ($t(34) = 1.19$, $p < 0.06$, $g = .41$) and Information (reading disabled ($M = 8.5$, $SD = 2.6$) controls ($M = 9.7$, $SD = 2.7$) mean difference 1.21 ($t(34) = 1.96$, $p = .06$, $g = .46$).

Rapid Picture Naming was selected due to dyslexics' inability to quickly and accurately retrieve phonetic information and pronounce the words for simple stimuli (Woodcock-Johnson II was used rather than III due to availability to the researchers).

The subtests from the WIAT III, Pseudoword, Oral Reading Comprehension, and Spelling were selected due to their associated deficits in dyslexia and the availability of a dyslexia-specific index in the Dyslexia Index Scores Manual (2018)

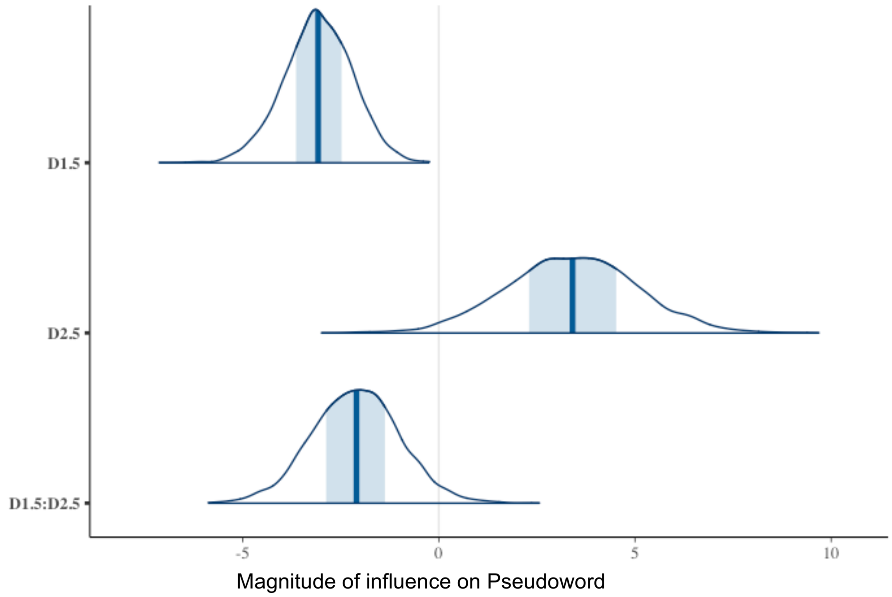
Appendix I: Effect of the operating system on RT data collection

This result was not intuitive with the prior analysis predicting Pseudoword, so the analysis was run again without the five dyslexic subjects that did not complete Symbol Search. When those subjects were removed, there was strong evidence for the full model, D1.5 + D2.5 + D1.5:D2.5, predicting Pseudoword, BF= 13.5 over intercept only (Figure 19). It had weak evidence over the next two best models: BF (D1.5)=1.3 and BF(D1.5+ D2.5)=1.6. This analysis was repeated for controls only and without the three control subjects who did not complete Symbol Search. The strongest model, D2.5 over intercept only, had minimal evidence against its inclusion, BF=0.68 over intercept predicting Pseudoword. The following model, D1.5, was taken under the strongest model, D1.5, and there was minimal evidence against it, BF=1.05.

The javascript code used "window.navigator.platform" to which will only return "MacIntel", "Win32", or "Linux x86_64". OS Chrome returns the default of "Win32" so verification of OS is only through the experimenters' notes of why Symbol Search was not completed and the experimenter did not document each subject's OS initially. Further investigation of the OS effect on response time data collected online could be useful. Bridges, Pitiot, MacAskill, and Peirce (2020) found recorded RT differences based on presentation lag based on the experiment platform, operating system, and browsers. To investigate if any effect of OS or browser could be assessed, the users who did not complete Symbol Search and script returned "MacIntel" was added back to the dataset, some support for the Pseudoword hypothesis returned, BF(D1.5.+D2.5)=7.3 over intercept and BF(D1.5)= 3.6 over intercept (Figure 20).

Figure 19

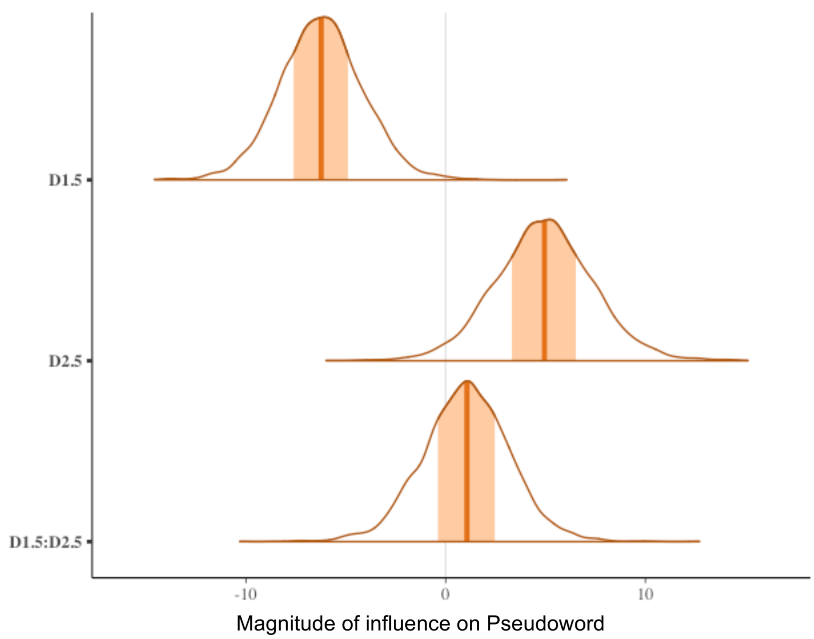
Marginals of the predicted posterior for the model Pseudoword~ D1.5 + D2.5 + D1.5:D2.5 for the five-spaced condition for dyslexics (who completed Symbol Search; n=16)



Note. The relative influence of the factors predicting Pseudoword showing D1.5 having the strongest influence on the dependent variable.

Figure 20

Marginals of the predicted posterior for the model Pseudoword~ D1.5 + D2.5 + D1.5:D2.5 for the five-spaced condition for dyslexics (who were not on Chrome; n=18)



Note. The relative influence of the factors predicting Pseudoword showing D1.5 having the strongest influence on the dependent variable.