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The Effects of Visual Attention Span and Phonological Decoding in Reading Comprehension in Dyslexia: A Path Analysis

[Key Words]: Visual Attention Span; Dyslexia; Reading Comprehension

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Abstract: Increasing evidence has shown visual attention span to be a factor, distinct from phonological skills, that explains single word identification (pseudo-word/ word reading) performance in dyslexia. Yet, little is known about how well visual attention span explains text comprehension. Observing reading comprehension in a sample of 105 high school students with dyslexia, we used a pathway analysis to examine the direct and indirect path between visual attention span and reading comprehension while controlling for other factors such as phonological awareness, letter identification, short term memory, IQ and age. Integrating phonemic-decoding-efficiency skills in the analytic model, this study aimed to disentangle how visual attention span and phonological skills work together in reading comprehension for readers with dyslexia. We found visual attention span to have a significant direct effect on more difficult reading comprehension, but not on an easier level. It also had a significant direct effect on pseudo-word identification, but not on word identification. In addition, we found that visual attention span indirectly explains reading comprehension through pseudo-word reading and word reading skills. This study supports the hypothesis that at least part of the dyslexic profile can be explained by visual attention abilities.

Developmental dyslexia is estimated to occur in 10% to 15% of the population in English speaking countries (Lyon, Fletcher, & Barnes, 2002; Shaywitz, et al., 1992). An impairment in phonological processing, namely a deficit in the ability to identify, reflect upon, and store or retrieve the individual sounds in words, is predominantly accepted as the core mechanism of dyslexia (Vellutino et al., 2004; Olson et al., 1994). This explanation has been supported by (1) convergent reports that people with dyslexia perform below average in phonological awareness and auditory discrimination tasks (Bradley & Bryant 1978; Fletcher et al., 1994; Katz, 1986; Thomson & Goswami, 2009), (2) evidence that phonological awareness measured at preschool age can effectively predict future reading performance (Bradley & Bryant, 1983; Torgesen, Wagner & Rashotte, 1994), and (3) evidence that intervention studies training people with dyslexia on phonological awareness and rhythmic processing can effectively improve their word-identification and reading performance (Bradley & Bryant, 1983; Fox & Routh 1976; Thomson, Leong & Goswami, 2012). Phonological processing deficits are believed to result in difficulties in phonemic or letter-sound decoding (Blau et al, 2009), which in turn, impact word identification performance and subsequent reading comprehension (Vellutino et al., 1991, 1994; Snowling, 2000; Blachman, 2000; Stanovich, 1991).

Alternative explanations of dyslexia have proposed that visual processing plays a key role, and these models have been hotly debated since the first definitions of dyslexia in the early 1900s. Recent research has confirmed that literacy skill is not only associated with enhancement in phonological activation but also in visual responses (Dehaene, et al, 2010). A meta-analysis by Jobard and Tzourio-Mazoyer (2003) concluded that early visual analysis and the visual word form system are necessary for grapho-phonological and lexico-semantic processing during graphemic parsing (Jobard & Tzourio-Mazoyer, 2003; McCandliss, Cohen & Dehaene, 2003; Warrinton & Shallice, 1980). In addition, it has been demonstrated that a deficit in serial letter scanning, controlled by the dorsal visual attention stream (from the posterior parietal cortex), leads to the impairments in visual processing of graphemes and their translation into phonemes (Vidyasagar & Pammer, 2010; Facoetti et al, 2010). Increasing debates have been spurred between vision and phonology scientists over how much variation in dyslexia can be attributed to visual impairments. On one hand, visual research has shown evidence that: (1) people with dyslexia are potentially impacted by sluggish attention shifting (Lallier et al, 2010), a condition in which a reader fails to quickly shift from one visual stimulus to the other (Hari & Renvall, 2001; Roach & Hogben, 2007); (2) readers with dyslexia are more affected by the crowding effect (Callens et al., 2013; Spinelli et al, 2002) - the crowding effect is a common visual effect in which reader cannot read a letter in their peripheral vision if the letter is embedded between other letters. Equally, increasing the letter spacing (reducing the crowding effect) can effectively improve reading in dyslexia (Zorzi et al, 2012; McCandliss, 2012; Gori & Facoetti, 2015; Martelli et al., 2009); (3) Recent studies have shown that pre-reading visual attention function as measured by serial searching and spatial cueing tasks can predict reading skills in grade 1 and 2 (Franceschini et al, 2012; Plaza & Cohen, 2007); (4) Moreover, treatments specifically training visual attention skills are reported to improve not only word reading in children with dyslexia but also their pseudo-word decoding skills (Franceschini et al, 2013). On the other hand, however, visual attention deficits are often reported to be comorbid with deficits in phonological skills (Borsting et al., 1996; Cestnick, 2001; Cestnick &

Coltheart, 1999; Vellutino et al., 2004; Eden & Zeffiro, 1998; Shaywitz & Shaywitz, 2008), and visual deficits alone do not consistently explain the variance in tests of word identification (Vellutino et al., 1994). As a result, visual explanations of dyslexia are often considered to be confounded by phonological deficits (Vellutino et al., 2004; Eden & Zeffiro, 1998; Facoetti, et al., 2005; Facoetti, et al. 2003).

More recently, Bosse, Tainturier and Valdois (2007) have proposed the visual attention (VA) span deficit hypothesis that sets out to reconcile the confounding relationship between visual and phonological processes. VA span is defined as the number of distinct visual elements that can be processed in parallel, in a multi-element array within the first 200 ms (Bosse, et al., 2007). Operationally (as introduced in detail in method section), 5 evenly spaced (about 0.6cm) unique letters (20 point) would appear for 200ms, and the participants were asked to report as many as they can. In our previous pilot study with college freshmen, typical readers scored 3.7 whereas dyslexic readers scored 3.0 (sd=0.25). Various studies have found VA span to explain unique variance in single word reading performance controlling for phonological awareness, phonological decoding skills and working memory (Bosse, Tainturier & Valdois, 2007; Bosse & Valdois, 2009; Lallier, Donnadieu & Valdois, 2012; Lallier, Donadieu, Berger & Valdois, 2010; Lallier, Thierry & Tainturier, 2013). This hypothesis can also explain the observation that emerging and dyslexic readers have difficulty in reading long words or pseudo-words that require a wider visual attention span, known as the length effect (van den Boer et al., 2013; Zoccolotti et al., 2005; Rastle & Coltheart, 1998). A recent study has shown that short lines improve reading for a particular group of readers with dyslexia who have short VA span (Schneps et al, 2013a). To explain the VA span deficit hypothesis for dyslexia, Ans, Carbonnel and Valdois (1998) proposed a multi-trace memory (MTM) model that enables successful word reading: an analytic procedure that focuses on sub-lexical units, which is important for phonological decoding, and a global procedure that requires distributed attention, which relies on VA span, extending over a long string of letters or segments. A large VA span facilitates capturing and connecting between units and "moderate reduction of the VA window size prevents reading in global mode" (Bosse et al, 2007, p201), and force the reader to use the analytic, more phoneme-by-phoneme mode instead. The MTM model further predicts that the analytic mode of reading also depends on VA span because parallel processing of multiple-letter sub-lexical units is necessary for analytic processing (Ans, Carbonnel & Valdois, 1998; Bosse & Valdois, 2009). A VA span reduction impairs multi-letter processing so that the whole letters of long graphemes cannot be simultaneously captured. This will further impede the process of graphemes from being assembled into units that can be parsed as phonemes, and from there words (Vidyasagar & Pammer, 2010; Schneps et al., 2013a,b). As a result, what is rooted in the deficit of visual attention span can manifest as the inability to process or decode an array of graphemes. In brief, VA span can contribute to reading via a network which sometimes process the word sequence as a whole (global procedure) and sometimes focus on sublexical units through seral processing (analytic procedure).

Visual Span, Perceptual Span, and Visual Attention Span

It has been understood for some time (Huey, 1908) that there is a limit to the number of characters that can be perceived in a glance, and that, therefore, there is a critical interplay between visual perception and eye movements during reading. These concepts have undergone many generations of redefinition and refinement (Bouma, 1970;

Motter & Belky, 1998; Vlaskamp, Over, & Hooge, 2005). [Excellent reviews of the history of this research are found in Pelli et al., (2007) and Legge et al. (2007).]

This research makes a distinction between "visual span" as defined by Legge (1997) and "perceptual span" as defined by (McConkie & Rayner, 1975; Rayner & McConkie, 1976). While the former considers the number of characters that can be perceived at a glance in the absence of eye movements, the latter considers factors affecting the perception of text during eye movements, accounting for the influence of text perceived in parafoveal locations. The visual attention (VA) span measure as proposed by Bosse, Tainturier and Valdois (2007) relates to these formulations, but the relationship between VA and "visual span" or "perceptual span" differs in important ways that have yet to be established.

Theories of visual span are motivated by the observation that text can only be accurately discerned in a window surrounding the locus of fixation, and that text perceived in the parafovea and periphery is dramatically less informative when it comes to reading (Rayner & Bertera, 1979). Legge et al. (2001) defined visual span as the number of characters in a line of text that can be read in a single fixation. In other words, visual span is conceptualized as the window about the fixation point through which text can read. Given that only a limited number of characters are perceived in this window at a glance, the locus of fixation needs to be updated to read words arrayed in a sentence. Provided that gaze advances at a constant rate (Huey, 1908), the larger the visual span, the faster will be the reading speed (Legge, 2007; Legge et al., 2001).

It was recently explained that one reason there is a limit to the number of characters able to be perceived at a glance is because of a long-range interaction phenomena in vision known as crowding (Bouma, 1970; 1973; Pelli et al., 2007). When similar visual objects, such as letter forms, are perceived in the periphery, the identity of the cluttered objects are more difficult to discern, when compared with their perception in isolation. This crowding,effect increases with increasing peripheral angle, a functional characteristic known as Bouma's law. When applied to letters, crowding is observed to be independent of letter size, and it is ordinarily influenced only by the letter spacing and the peripheral angle at which the letters are perceived relative to fixation. This phenomenon gives rise to what Pelli, et al. (2007) referred to as an "uncrowded span" of text surrounding fixation. Outside the uncrowded span, text cannot be accurately perceived due to limitations imposed by crowding. Pelli et al. (2007) demonstrated that the "visual span" as defined by Legge et al., is equivalent to the "uncrowded span" determined by crowding.

Operationally, Legge's visual span task (Legge et al., 2001) measures the eccentricity at which a trigram (three random letters) can be accurately reported. Here, RSVP is used to briefly flash trigrams at various eccentricities to observe response accuracy as a function of angle. Perceptual span, as defined by McConkie & Rayner (1975), differs in that this method typically uses a gaze contingent display to alter the text at various angular distances from fixation as the gaze advances in normal reading. This method allows the observation of the effects of the manipulation on reading speed and eye movements (e.g., regressions). Using this technique, it was found that information in the parafovea is used during reading to guide attention and otherwise improve reading (Inhoff and Rayner, 1986).

Of the two methods, VA span is conceptually closer to Legge's original definition for visual span in that VA span has been assumed to measure the number of letters one can perceive at a glance. A number of variants of the VA span task have been used in the literature, and in this study we use an implementation as originally described by Bosse et al., (2007) calling for a simple global report in response to a briefly presented non-informative letter string 6 characters long. In this version of the task, the characters are widely spaced., VA span differs from the visual span of Legge et al., in a number of important respects. (1) Given that the letters are widely space, the influence of crowding is diminished in the VA span task. (2) While the visual span explicitly measures response to trigrams at well-defined eccentricity, the VA Span task is a global report, and the eccentricity of the target letters is not considered in the total score. (3) VA span is typically assessed through tasks of global and partial report. The partial report only asks participants to report the one letter probed by a cursor after the presentation of stimulus in order to exclude problem with single letter processing. (4) Finally, and perhaps most importantly for applications relevant to dyslexia, the procedures of Legge et al., only present three letters at time, while the global report task here requires respondents to distribute attention to a span of consonant arrays containing twice as many letters. Thus, the VA span task, unlike the visual span, is sensitive to variations in distributed attention among the participants, and this may be important in dyslexia.

Rationale for this study

The relationship between the VA span task and the visual span is an open question that needs to be explored in depth through future study. However, given that a number of studies have shown that the VA span task is useful in contexts related to dyslexia, the task is potentially powerful because it can be easily administered *in situ*, by teachers in an educational context. In this study, we used a novel method for presenting the VA span stimulus that was designed for use in schools. It uses custom software running on an inexpensive handheld device (Apple iPod Touch) to permit data collection in school settings with little specialized training. Previous studies in our laboratory (Schneps, et al., 2013a,b) showed that this measure is useful in separating those participants with dyslexia who benefit from augmented text formatting from those who do not. Thus, this implementation of the VA span task may constitute a promising tool to guide the evaluation and treatment of students with dyslexia.

It is noteworthy that in all of the previous VA span studies, "reading skill" is equivalent to, and *only* measured by, word/pseudo-word identification tasks. The relationship between VA span and text reading has been explored (Prado, Dubois & Valdois, 2007; Lobier, 2013), but not with reading comprehension, the ultimate goal of reading. No study, to our knowledge, has examined how well VA span can predict text comprehension, the ultimate goal of reading. Little is known about whether VA span can directly explain reading comprehension controlling for phonological and word-identification skills, or indirectly explain reading comprehension via whole word-identification skills. In addition, if the proposed hypothesis that VA span facilitates reading by capturing a wider range of written segments is correct, it should not only help binding graphemes within word level, but also help binding between words at the sentence level.

Current Study and Research Questions

Since the MTM model predicts that VA span contributes to reading via two procedures of the same network, one that directly explains reading (global mode) and another one indirectly via phonological decoding skills (analytic mode), it is necessary to adopt an analytical approach that distinguish the two procedures. Therefore, in this study, we used path analysis (Stage, Carter & Nora, 2004; Edward & Lambert, 2007) to examine how well the VA span directly and indirectly explains different levels of reading comprehension in addition to (controlling for) the phonological awareness explanation. Our two primary research questions are:

In a group of high school students with dyslexia, in comparison to phonological awareness, 1) does VA span have a total effect (the sum of direct and indirect effect) on reading comprehension? How much of the total effect is mediated by word identification and phonological decoding? Alternatively, is there a direct effect not mediated by word identification and phonological decoding? 2) Does VA span have a total effect on phonological decoding and word identification? How much of the total effect on word identification is mediated by phonological decoding? Is there a direct effect not mediated by phonological decoding?

This study is a within-dyslexia-group examination. It does not compare dyslexic and typically-developing readers. We ask the specific question as to whether shorter VA spans are associated with greater reading comprehension difficulty among dyslexic readers who have already shown delayed development in phonological awareness and phonological decoding skills. If a poor VA span adds an additional obstacle to reading comprehension among readers with dyslexia, our study would suggest that there is a potential sub-group within the dyslexic population whose difficulties in reading comprehension are made more severe by a combination of phonological and VA span deficits. Recent research demonstrates that visual accommodations specifically benefit dyslexic readers who have short VA spans (Schneps et al, 2013a, b). Prompt diagnosis and accommodation of VA span deficits will thus benefit those who struggle the most with reading comprehension but also potentially have the most to gain from personalized intervention regimes that address both visual and phonological needs. For this reason, the goal of this paper is to investigate the previously unresearched link between VA span and reading comprehension within the dyslexic population. By demonstrating the importance of VA span for reading comprehension in readers with dyslexia, we pave the way for future studies to compare dyslexic and normal reading populations and investigate whether the role of VA span in reading comprehension is a dyslexia-specific mechanism.

Methods

Participants

105 high school students with a lifelong history of reading difficulties (39 female, 66 male, with a mean of age at 17, sd = 1.2) were recruited from Landmark High School, in Beverly (MA), USA. It is a private high school exclusively for students with reading disabilities. Students had a diagnosis from a neuropsychologist, who documented (a) a specific reading disability (b) average or above average non-verbal IQ, and (c) the absence of a neurological impairment, as required by the enrollment criteria for the school. Students who had a diagnosis of ADHD from a neuropsychologist (reported in their school documents) were excluded from this study.

Participants in the sample were recruited for an intervention to support reading.

We examined performance on VA span, reading comprehension and additional academic and cognitive tests administered to this sample. The data used in this sample is collected before they receive the intervention. As shown in Table 2, the reading measures of the sample ranked at the bottom of the age norm, while nonverbal IQ (block design) ranked around the average. Although every participant had a diagnosis of developmental dyslexia from a neuropsychologist, and we have re-confirmed that they had poor reading measures and normal IQ indeed, we want to remind the readers that we did not systematically evaluate perinatal disorders, ADHD symptoms (those who had an ADHD record were excluded), auditory and visual acuity. It was decided to concentrate on students with a diagnosed reading disability in the first instance, as this is a population where a) the contribution of visual factors to reading ability is most contested and b) demonstration of a link between visual attention and reading comprehension would have the most practical value in terms of potentially adapting text to enhance reading ability in struggling readers. Due to a stipulation of the funder, control data from typical readers was to be collected in a subsequent study, and thus is not available for this paper.

High school students were sampled because it is an age that students are exposed to a lot of new, specialized and increasingly multi-syllabic vocabulary items and therefore potentially a period in which VA span is particularly important.

Measurements

Reading Comprehension

Reading comprehension was measured by Gates-MacGinitie Reading Test (MacGinitie et al, 2000). Here we followed procedures recommended in the testing manual. Accordingly, the reading time for this task was constrained to 35 minutes. The test consists of numerous passages. Following each passage, multiple-choice questions are used to gauge reading comprehension. The reasons for choosing this test were (1) it has the difficulty levels sensitive to the age group in the sample; (2) the multiple choice questions result in an objective scoring method; (3) the format of the tasks between different difficulty levels are the same; and (4) the total raw score are the same between different difficulty levels and both scores can be converted to national norms. Students were tested using items designed for both levels 7 and 10 so as distribute sensitivity over a large span of potential reading ability. Each level has 12 passages for reading comprehension. As measured by Lexile (MetaMetrics, 2013), level-7 has less load of reading demand in terms of semantic difficulty and syntactic complexity than level-10. In addition, level-7 has shorter sentences and slightly fewer letters per word compared to level-10 (Table 1). The score for each level was the number of comprehension questions answered correctly. Such difference between level-7 and level-10 allows us to examine if VA span affect levels of reading demand differently.

Table 1

Word Reading

The word reading task was excerpted from the second edition of the Test of Word Reading Efficiency (TOWRE-2), also known as word reading. It assesses the number of single words an individual can accurately identify and read aloud within 45 seconds. The raw scores were converted to standard scores based on national norms provided by the TOWRE-2 manual (Torgesen, Wagner & Rashotte, 2012).

Pseudo-word Reading

Similar to the word reading task, the pseudo-word reading task was also excerpted from the TOWRE-2. It measures the number of pronounceable non-words that an individual can accurately read aloud in 45 seconds. It is an indicator of phonological decoding skill. The raw scores were converted to standard scores based on national norms provided by the TOWRE-2 manual (Torgesen, Wagner & Rashotte, 2012). Timed measures were used to capture both accuracy and automaticity. Once individuals are beyond the basic stages of word reading, timed approaches are typically more sensitive to measure word identification skills.

Elision

In this study, we used the Elision subtest, a 20-item measurement of phonological awareness, taken from the Comprehensive Test of Phonological Processing (CTOPP). It measures a participant's ability to repeat words while deleting designated phonemes. For example, to say "tiger" without saying /g/ is "tire". The number of correct responses was then converted to a standard score based on the national norms provided by the CTOPP (Wagner, Torgesen, Rashotte, 1999).

Visual Attention Span

The VA span task was administered using custom presentation software (iCue) on a third generation Apple iPod touch device (10.92cm high, 6.10cm wide, 8.89cm diagonally wide). The device has a screen resolution of 640 x 960 pixels at 128 pixcels per cm. The luminance was set to a black level of approximately 1.27 cd/m^2 and a white level of 127.3 cd/m^2. The image displayed by iCue were generated by computer using custom sofward written in Matlab. Ambient room luminosity was between 314.0 lux and 423.0 lux. Students freely held the device in their hand at a comfortable distance (approximately 35 cm from the eye). To start each trial, the participants tap on the iPod's touchscreen. A centrally-placed fixation marker would appear for 1000 ms, followed by a blank screen of 500 ms. We measured device latencies using an oscilloscope and photodiode prior to the experiment, and the software was adjusted to compensate. The device was taken offline, and other applications turned off to help ensure a stable platform during presentation.

Following procedures as described in Bosse (2007), 6 unique letters (Courier font, fixed width 18 pixels and height 24 pixels) each separated by 99 pixels would appear immediately for 200ms. The total length of the string spanned 521 pixels, and the string was centrally placed on the screen. In each trial, the 6 letters were chosen randomly with no order constraint from a letter set (letter set: D, M, R, F, B, P, T, H, L, S. Consonants were chosen to prevent the possibility of pronounceable words resulting from the string). After the 200ms duration, a blank screen would appear. In the *VA span task*, the participants were asked to report all the letters they could recall, regardless of order. The participants were told to do the best they can, but they were not pressured to always report 6 letters. In *partial report task*, the participants were asked to report the one letter indicated by a probing cursor after the presentation of the string. After reporting, the participant tapped on the touchscreen to proceed to the next trial. A total number of 24 trials were presented for the VA span task and 72 trials for the partial report tasks. Each task was scored separately. For the VA span task, the participant scored 1 for each letter correctly recalled in each trial. The participants were not scored on whether letters were reported in the correct order. The final score is the average score. For the partial report task, the participant only needed to report one letter and score 1 if reported correctly. The final score is averaged, so that an average of 0.6 means 3.6 letters can be accurately identified on a array of 6 targets.

At the beginning of the task, the administrator made sure that the participants were holding the iPod 35 cm from their eyes and asked them to maintain this distance while and avoiding moving their bodies. Here, a chin rest was not used to restrict the distance because this would have hindered the students' ability to verbally report their response at the end of each trial. Given that this procedure may introduce variations in the device-eye distance, we conducted a follow up study to investigate the effect of distance on VA span score. Here, using a chin rest to restrict movement, we tested 20 college-aged participants, and compared VA span at a device-eye distance of 35cm and 25cm. No statistically significant difference was observed between the two distances, suggesting that a 10cm movement in position would have negligible impact on the measured scores. In the original experiment, a 10cm movement was noticed and corrected by the experimenter.

Memory for Digit

Memory for Digit was excerpted from CTOPP as well. It served as a measurement of short term memory. In each of the 21 trials in this task, the experimenter plays an audio track that reads a string of numbers (span range from 2 to 8) to a participant. Afterwards, the participants repeat the numbers in the same order. The participant scores 1 point each time he/she completes a trial without error. The raw score was later converted to a standard score based on the national norms provided by the CTOPP (Wagner, Torgesen, Rashotte, 1999).

Block Design

Block design is a test of non-verbal intelligence excerpted from Wechsler Abbreviated Scale of Intelligence (WASI, Psychological Corporation, 1999). In this test the participants use two-color printed cubes to replicate geometric patterns printed on a paper within the time limit. The participant is scored based on the time they used to complete each replication task. If the participant replicate incorrectly or exceed the time limit in a trial, the trial is scored 0. The raw score was converted to a standard score based on the norms provided by WASI manual (Psychological Corporation, 1999).

Hypothesized Model and Data analytic approach

In step 1, we used Mahalanobis distance to detect multivariate outliers. We did not find any outlier when 15 percentile (a rather strict criteria) of the chi-squared distribution was used as the threshold.

In step 2, we used path analysis to model the relationship among the variables measured above. Path analysis is particularly useful in the modeling of mediation and in comparing the effects of different factors, via different paths, to the outcomes. We examined the fitness and loadings in the hypothesized path model. The hypothesized model specifies two pathways (shown in Figure 1 with solid arrows only) to reading comprehension: a phonological path and a VA span path. In the phonological path, we specified that Elision, a measure of phoneme-segmentation skill is a precursor of pseudo-wording reading, and pseudo-word reading, a measure of phonological decoding skill, is a precursor of word reading. Finally, word reading skill will be the direct predictor for the scores in levels 10 and 7 of the Gates-MacGinitie Reading Comprehension Test. We separated the comprehension scores in level-7 and level-10 instead of using the composite score of the two because we intended to examine if the cognitive skills (especially VA span) may affect passages with different word and sentence loadings differently. We also allowed Elision to directly explain word reading and both levels of reading comprehension. The loadings of each of the paths in the phonological route will serve to validate the phonological awareness explanation of dyslexia with the sample of 105 participants. Building on the phonological route, we added a path from VA span to (a) levels 10 and 7 reading comprehension, and (b) pseudo-word and word reading. This route serves to examine the VA span explanation for word identification and text comprehension controlling for phonological awareness.

In step 3, in case the effect of VA span is confounded by IQ, short-term memory, or letter identification within strings in the global report task, we added measures of block design, memory for digit and partial report to the model for validation (as shown in Figure 1 including dashed arrows). In brief, we tested the model with solid arrows to answer our key research question while including the dash arrow to rule out potential confounding variables. Typically, a single letter processing task is taken to control for letter processing. If single letter processing is preserved, the performance in global and partial report mainly reflects the way attention distributes over the letter array. However, we did not administrate the single letter processing task (as will be discussed in the limitation section), instead we used the partial report task as a proxy for letter identification modulated by visual attention when letters are displayed within strings. In other words, partial report is considered as letter identification with visual attention span activated.

In step 4, we considered two alternative models (explained by the end of the result section): one that did not specify a directional path from pseudo-word to word reading but allowed the two covary, another one that placed IQ and age as the exogenous predictors for all other variables (including the cognitive and reading skills), while keeping the paths from cognitive to reading skills the same.

Figure 1

Results

Table 2 presents the descriptive statistics of all variables.

Table 2

Table 3 presents the correlation and covariance matrices of the eight variables. The matrix was used to determine whether the hypothesized model (Figure 1) fit the data. model-fit indices reached a consensus of a good overall model fit: the Chi-Square model fit was $\chi^2_{(11, 105)} = 14.90$ ($\rho = 0.19$); the root mean square error of approximation (RMSEA) was 0.06 within a confidence interval range from 0 to 0.15; the standardized root mean square residual (SRMR) is 0.04; and the CFI is 0.97. We retained the non-significant paths because they were important to test our hypothesis and keep potential confounders controlled for (even though most of the control variables were not significant). Therefore, we did not modify our proposed model (see Figure 2 for the model with coefficients that are statistically significant and their standardized loadings).

Table 3

Figure 2

Table 4 shows the parameter estimates of each path in the model. VA span had a direct effect on pseudo-word reading (PD) (est. = 4.207, S.E. = 1.604, $\rho = 0.001$) and level-10 reading comprehension (est. = 10.240, S.E. = 4.693, $\rho = 0.020$). To more directly test the hypothesis that VA span directly contributes to reading comprehension, we compared the current models with a reduced model that does not allow direct link from VA span to level-10 reading comprehension (every other path is specified the same). The current model had a significant better fit than the reduced model ($\chi^2_{(1)} = 4.62$, $\rho = 0.03$). The direct effects from VA span to word reading (WR) (est. = 0.152, S.E.=1.736, $\rho = 0.29$) and level-7 reading comprehension (est. = 3.116, S.E.= 5.350, $\rho=0.56$) were not statistically significant.

In addition, word reading had a direct effect on both level-10 (est. = 0.811, S.E. = 0.279, $\rho < 0.01$) and level-7 reading comprehension (est. = 1.262, S.E. = 0.319, $\rho < 0.001$). Pseudo-word reading had a direct effect on word reading (est.= 0.603, S.E. = 0.122, $\rho <0.001$).

In contrast to VA span, Elision (ELI) did not have significant direct effect on either level-10 (est. = 0.154, S.E. = 1.231, $\rho = 0.90$) or level-7 (est. = 1.871, S.E. = 1.420,

$\rho = 0.18$) reading comprehension. Elision did not have a direct effect on word reading (est. = -0.122, S.E. = 0.440, $\rho = 0.78$), and only marginally on pseudo-word reading (est. = 0.733, S.E. = 0.408, $\rho = 0.06$).

Table 4

Table 5 shows each of the indirect effects in the model, from VA span and Elision (a measure of phonological awareness) via pseudo-word reading (a measure of phonological decoding skill) and word reading to reading comprehension in levels 7 and 10 via word reading. The indirect effects from Elision on both levels of reading comprehension were not significant. Elision only had a marginally significant indirect effect on word reading. The indirect effects from VA span to two levels of reading comprehension via only word reading were not statistically significant, but the indirect effects from VA span on both level-7 (unstandardized effect = 3.200, S.E. = 1.600, $\rho = 0.04$) and level-10 (unstandardized effect = 2.055, S.E. = 1.135, $\rho = 0.07$) reading comprehension via pseudo-word reading and word reading were marginally significant around the level of 0.05. As can be seen in the comparison of the standardized effects of VA span and Elision in Table 5, VA span had consistently larger direct and indirect effects on word identification and reading comprehension than Elision.

Table 5

To validate that the relationship between VA span and reading performance was not confounded by letter identification under distributed attention, rapid naming skills, short-term memory, age or IQ, we added the participants' age and scores in partial report task, memory for digits (retrieved from CTOPP), rapid letter naming and block design as covariate to the model, with their paths pointing to both levels of reading comprehension. Block design had a significant effect on reading comprehension (for level-10, unstandardized effect = 0.498, S.E. = 0.273 $\rho = 0.06$; for level-7, unstandardized effect = 0.854, S.E. = 0.312, $\rho < 0.01$). Rapid letter naming has significant effect on word reading (unstandardized effect = 0.946, S.E. = 0.446 $\rho = 0.03$) and pseudo-word reading (unstandardized effect = 1.438, S.E. = 0.2322 $\rho < 0.01$). Other control variables did not have significant paths. Adding such covariates did not change the effect of VA span concluded in the above model.

We also considered two alternative models. First, Peterson, Pennington & Olson (2013) has shown that pseudo-word reading and word reading might dissociate in developmental dyslexia and that the dissociation rate increases with age. So it was theoretically reasonable to consider that pseudo-word and word reading may be dissociated, especially in the sample of high school students. Therefore, we tested an alternative model that allowed pseudo-word reading and word reading skills to mediate the effect of VA span in parallel (rather than in a chain). The alternative model, however, had a poor models fit ($\chi^2_{(9, 105)} = 34.345$, $\rho < 0.01$; RMSEA = 0.19; CFI = 0.783; SRMR = 0.091), the primary reason was that pseudo-word reading had a low correlation with reading comprehension in the sample. Second, rather than placing fundamental predictors such as age and IQ at the same level of specific cognitive skills, we considered a model in which age and IQ may predict other cognitive and reading skills. Such an alternative model led to a poor model fit ($\chi^2_{(18, 105)} = 41.727$, $\rho < 0.01$; RMSEA = 0.13; CFI = 0.853; SRMR = 0.090). Nevertheless, the effect regarding to VA span remained roughly the same (significant on level-10 reading comprehension and pseudo-word reading, but not on level-7 reading comprehension and word reading).

In summary, VA span had a statistically significant direct effect on level-10 reading comprehension, but not on level-7 reading comprehension; VA span also had a direct effect on pseudo-word reading but only an indirect effect on word reading. VA span was mediated by phonological decoding skill to have an indirect effect on word identification and reading comprehension. Elision did not have a direct effect on either level of reading comprehension. It only had a marginally direct effect on pseudo word reading, and was mediated by pseudo word reading to have an marginally indirect effect on word reading and reading comprehension. In addition, the effects of VA span on word and text reading could not be explained by age, non-verbal IQ, letter identification and short term memory.

Discussion

The resulting model confirmed literature findings (Mellard, Fall & Woods, 2010; Vellutino et al, 2007; Swank & Catts, 1994) that suggest that phonological awareness (measured by Elision) significantly contributes to phonological decoding of pseudo-words, phonological decoding significantly contributes to the ability to read words, and the word identification is an immediate contributor to reading comprehension.

These findings also confirmed published evidence (Bosse, Tainturier & Valdois, 2007) that VA span explains unique variance in phonological decoding controlling for phonological awareness. Bosse, Tainturier and Valdois (2007) concluded that VA span contributes to both word reading and pseudo-word reading which was agreed with through the pairwise correlation in our study, as shown in Table 2. Our finding also converged with previous evidence that visual spatial attention is more essential for pseudo-word reading than for word reading (Sieroff et al., 1988; Ladavas et al., 1997; Auclair & Sieroff, 2002; Facoetti., 2006). Our study results further showed that VA span explains word reading exclusively through the indirect path via phonological decoding. Results from our analysis showed that the effect of VA span on word reading via phonological decoding was similar (slightly larger) to the effect from phonological awareness (Elision) to words reading via phonological decoding, suggesting that both VA span and phonological awareness aid the analytical approach of word identification. In contrast to VA span, phonological awareness, as measured by Elision, did not have a statistically significant direct effect on reading comprehension. It only had a direct effect on phonological decoding, via which it had an indirect effect on word identification. Elision didn't have a significant direct effect on reading comprehension, and its indirect effect was marginal. In other words, the effect of Elision was fully mediated by phonological decoding and word identification.

Beyond confirming published research evidence, this study provided two new and important findings. Firstly, VA span had a statistically significant direct effect on reading comprehension at the more difficult level. Since we controlled for word identification in the analysis, these findings suggested that VA span explains reading comprehension beyond the single-word level, perhaps at the level of phrase or sentence. Secondly, VA span did not have a statistically significant direct effect on reading comprehension at the easier test level. In other words, VA span only had a direct effect on the difficult level of reading comprehension but not for the easy level (neither level-7 nor level-10 reading comprehension test had a ceiling or floor effect).

Our current data did not provide direct evidence to explain the reason that VA span contributes to pseudo-word reading (but not word reading) and the difficult level reading comprehension (but not the easy level). However, this finding is consistent with multiple existing hypothesis. We will try to apply these theories to explain our finding, although it is noteworthy that the explanations remain speculative. More studies are needed to examine the hypothetical claims. Our finding supported the visual attention deficit theory hypothesis (Bosse et al., 2007) and the length-effect theory (van den Boer et al., 2013) that one needs a wide visual attention span to quickly connect multiple phonemic units in one fixation in order to decode the whole word. If one fails to grasp multiple graphemes quickly, it will be difficult for the reader to combine the graphemes into units that can be parsed as phonemes, and then into a whole word. For such a reason, this difficulty could manifest as a phonological decoding deficit. A short VA span may also prevent one from capturing the upcoming visual element into the graphemic (visuospatial sketchpad), and eventually the phonological, buffer (Baddeley & Hitch, 1975; Baddeley, 2000). It may disrupt pseudo-word reading more than word reading because pseudo-word reading requires accurate tracing each phoneme and has higher demands on the graphemic buffer than real words (Tainturier & Rapp, 2003, Torgesen, Wagner & Rashotte, 2012). Furthermore, the visual cues in the visuospatial sketchpad are important to direct eye fixation. If one has a poor VA span due to a narrow visual span, the visual cues may fall out of the reading window, which leads to the failure to control eye saccades during reading (Bouma & deVoogd, 1974). It has been reported that short

VA span corresponds to more rightward fixation for dyslexic readers (Prado, Dubois & Valdois, 2007), which may suggest failure to locate rightward visual cues. Moreover, reformatting a wide line of text into short and multiple rows dramatically reduces the regression saccades (Schneps et al, 2013b) and improves reading comprehension for a subgroup of dyslexia readers with short VA span (Schneps et al, 2013a). This suggests that eliminating the need to look for visual cues in the rightward peripheral vision reduces the confusion one encounters when trying to distinguish between words, a particular difficulty made severe for those with short VA span.

We hypothesize that just as VA span helps one to connect letters and phonemes to decode a word, it may also help dyslexic readers make connections between words for successful reading. To comprehend a sentence, words and phrases must be combined fluently so that their meanings are not lost before the next words are processed (Curtis & Kruidenier, 2005).

Our data do not provide a direct explanation of this differences in effect. Based on the fact that the most difficult (level-10) reading comprehension tests contained longer sentences and a higher load of semantic difficulty and syntactic complexity than the level 7 reading tests (Table 1), it is reasonable to speculate that VA span is particularly useful for readers in grasping sentence segments with unfamiliar semantics or in connecting more words in complicated and long phrases. In comparison, simpler text has more sight words and simpler phrases and/or sentence structure so that readers do not need to correctly collect every piece of graphemic, phonemic and lexical information. Therefore, it reduces the readers' reliance on distributed attention to identify and bind such information. This pattern is analogous to the role that VA span plays in word identification (i.e., VA span explains pseudo-word reading better than word reading) as discussed above.

Limitations

It is noteworthy that the sample in this study is uncommon. All of the subjects were high school students enrolled in a special school for language impairment that provides long-term and intensive training focusing on phonological awareness. Given that those in this sample attended these programs for a minimum of 1 to 11 years (mean = 3.84, SD = 2.3), these participants represent a highly compensated sample. The role of VA span for younger or beginning readers, for whom phonological awareness is essential for the ability to read (Pennington & Lefly, 2001), is yet to be explored. We will also be cautious with generalizing the results of this study to the broader high school population with dyslexia. The phonological interventions received by the sampled students in the school specialized for students with dyslexia may reduce variability in phonological awareness, which may reduce its power as a predictor. For high school students with dyslexia who have not received intensive remediation in phonological awareness and phonological decoding skills, phonological awareness may contribute more variance to reading comprehension, and the strength and pattern of the VA span effect on reading comprehension may be different from this study's findings. In addition, we did not administrate the single letter identification task, and only used the partial report task as a proxy. As mentioned in data analysis section, typically, single letter identification task is tested to make sure single letter processing is preserved. While the partial report task controlled for letter identification modulated by distributed attention over letter string, we do not know if performance in this task is rooted in skills for identification of a letter when it is presented as a single unit. Finally, note that the direction of the arrow in the path diagram (Figure 1 and Figure 2) does not imply causality. They are postulations based on theory. Empirically, our data cannot answer the question as to whether students can improve reading comprehension by increasing their visual attention span. Future randomized controlled experiments and longitudinal data can better examine this question.

Conclusion

This study suggests that 1) word and pseudo-word identification have a significant VA span component. What has been considered a phonological decoding skill measured by pseudo-word reading task could be complicated by a compromised ability to quickly identify and connect graphemic units using visual attention; 2) VA span can operate within and beyond the single word level and can be activated when vocabulary, phrases or sentence structure is unfamiliar and/or very long. When words and sentences are short and simple, this process is not as critical because less binding is needed. The relationship between the response to visuospatial attention and the eponymous Visual Attention span task is as yet not well understood. Nevertheless, this study, linking previously unresearched relationship between VA span and reading comprehension, lends support to a growing body of evidence indicating that visuospatial attention plays a more important role in dyslexia than is often assumed. There is at least a sub-group of dyslexic reader whose reading comprehension are troubled by a combination of phonological and VA span deficits. Thus, comprehensive diagnosis and specific accommodation are necessary for those who struggle the most.

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Appendix

Table 1.

Mean and standard deviation of Lexile, sentence length, word count and word length of level-7 and level-10 reading comprehension tests.

	lexile measure	Sentence Length	Word count per passage	Word length
Level-7	1096.36 (165.30)	18.71 (5.04)	116.54 (28.72)	4.45 (2.24)
Level-10	1191.82 (204.88)	20.78 (5.56)	123.45 (38.31)	4.75 (2.66)

Lexile measure indicates semantic difficulty and syntactic complexity, it was measured using Lexile analyzing from lexile.com.

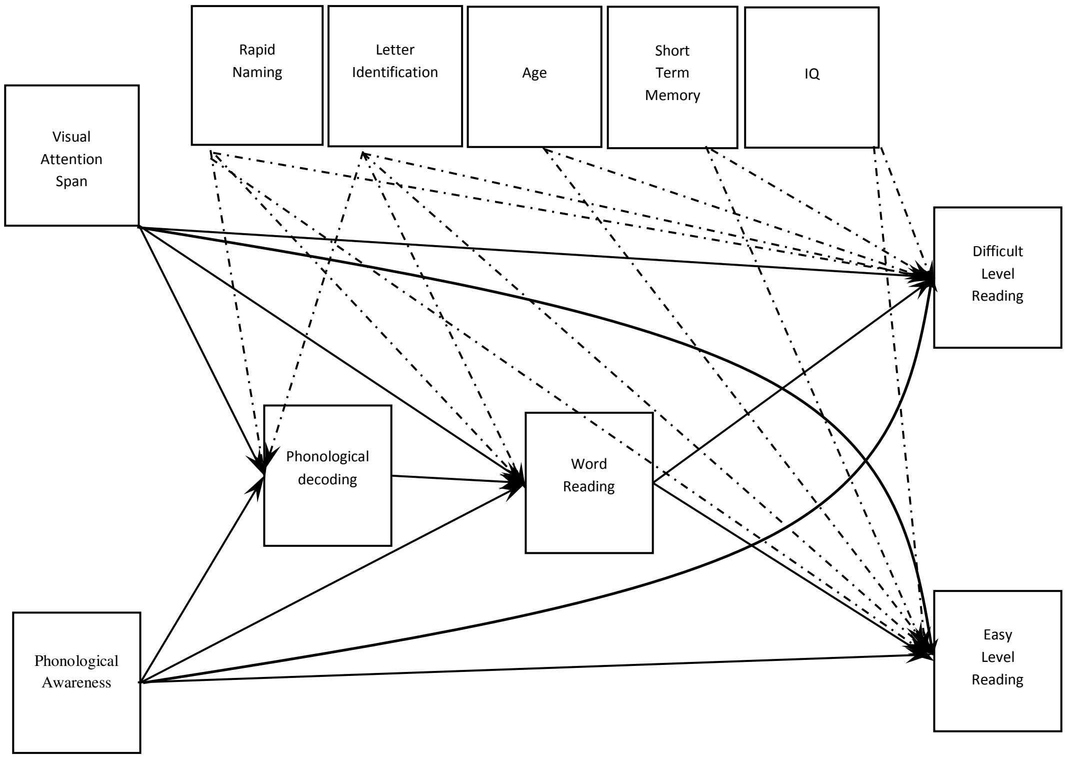

Figure 1. Path diagram for the conceptual model, in solid arrows, of reading comprehension explained by word identification (measured by word reading), phonological decoding (measured by pseudo word reading), phonological awareness (measured by elision task), and Visual Attention (VA) span. Age, IQ, short-term memory, rapid naming and letter identification are included, as shown with dashed arrows, to control for potential confounding relationship.

Table 2.

Descriptive statistics of variables

Variable	Mean	SD	Percentile: mean/(± 1 SD)
Elision (normed)	8.91	2.18	37 / (9-63)
Word Reading Efficiency (normed)	78.52	9.86	8 / (2-23)
Pseudo Word Efficiency (normed)	79.71	8.26	9 / (3-21)
Rapid Letter Naming (normed)	6.93	2.34	16 / (2-37)
Memory for Digit (normed)	9.15	2.99	37 / (1-16)
Block Design (normed)	47.38	10.28	53 / (27-82)
VA Span (global)	3.29	0.66	-
Partial Report Task	0.60	0.13	-
Reading comprehension, Level-7 (normed/raw)	537/30.55	32.9/9.41	Grade 8.5
Reading comprehension, level-10 (normed/raw)	544/23.11	26.7/9.12	Grade 9.1

In the last column, the first number is the percentile in the norm for the mean, the numbers in the parenthesis are the percentile in the norm for the score one standard deviation below and above the mean. The VA span and partial report tasks do not have norms, therefore their percentile score are omitted.
In the partial report task, an average of 0.60 means 3.6 letters can be accurately identified on a array of 6 targets.

Table 3

	1	2	3	4	5	6	7	8	9
1.Read10	-								
2.Read7	0.74***	-							
3.Word Reading	0.39***	0.41***	-						
4.Pseudo-word	0.13	0.20*	0.53***	-					
5. VA Span	0.28*	0.20*	0.27**	0.37***	-				
6. Elision	0.16	0.20*	0.12	0.29**	0.30**	-			
7. Memory digit	0.11	0.13	0.16	0.27**	0.15	0.05	-		
8.Block Design	0.23*	0.36***	0.06	-0.11	0.08	0.19	0.23*	-	
9. Partial Report	0.05	0.04	0.16	0.06	0.47***	0.14	0.04	-0.01	-
10. Age	0.13	0.12	0.03	0.16	0.10	0.06	0.07	0.18	0.02

The correlations are presented within parenthesis. Read10 is level-10 reading comprehension. Read7 is level-7 reading comprehension.
*.<0.05; **.<0.01; ***<0.001; the α level after Bonferroni correction for multiple test is 0.001.

Table 4

Path analysis parameter estimates, their unstandardized/standardized coefficients, standard errors and p-values for unstandardized coefficients.

Parameters	Unstandardized estimate	S.E.	P-Value	Standardized estimate
Read10-VA	10.240	4.693	0.02	0.255
Read10-WR	0.811	0.279	<0.01	0.298
Read10-BD	0.498	0.273	0.06	0.189
Read7-VA	3.116	5.350	0.56	0.066
Read7-WR	1.262	0.319	<0.001	0.396
Read7-BD	0.854	0.312	<0.01	0.277
WR-PD	0.603	0.122	<0.001	0.512
WR-VA	0.152	1.736	0.29	0.088
WR-ELI	-0.195	0.475	0.68	-0.043

PD-ELI	0.733	0.408	0.06	0.195
PD-VA	4.207	1.604	<0.01	0.336

Read10 is level-10 reading comprehension. Read7 is level-7 reading comprehension. VA is visual attention span. WR is word reading. PD is pseudo-word decoding. ELI is Elision, BD is block design.

Table 5

Direct effects and specific indirect effects, their unstandardized/standardized coefficients, standard errors and p-values for unstandardized coefficients.

Effects	est.	S.E.	p-value	Std. est.	Effects	est.	S.E.	p-value	Std. est.
DIR VA-Read10	**10.240**	**4.693**	**0.02**	**0.255**	DIR Read10-ELI	0.154	1.231	0.90	0.013
IND VA-WR-Read10	**0.123**	**1.408**	**0.93**	**0.003**	IND ELI-WR-Read10	-0.109	0.393	0.78	-0.009
IND VA-PD-WR-Read10	**2.055**	**1.135**	**0.07**	**0.051**	IND ELI-PD-WR-Read10	0.396	0.264	0.13	0.033
DIR VA-Read7	3.116	5.350	0.56	0.066	DIR ELI-Read7	1.871	1.420	0.18	0.130
IND VA-WR-Read7	0.192	2.191	0.93	0.292	IND ELI-WR-Read7	-0.159	0.573	0.78	-0.011
IND VA-PD-WR-Read7	**3.200**	**1.600**	**0.04**	**0.068**	IND ELI-PD-WR-Read7	0.578	0.371	0.12	0.040
DIR VA-WR	0.152	1.736	0.28	0.088	DIR ELI-WR	-0.122	0.440	0.78	-0.028
IND VA-PD-WR	**2.535**	**1.094**	**0.02**	**0.172**	**IND ELI-PD-WR-PD**	**0.445**	**0.262**	**0.08**	**0.102**

Bold rows are (marginal) statistically significant.

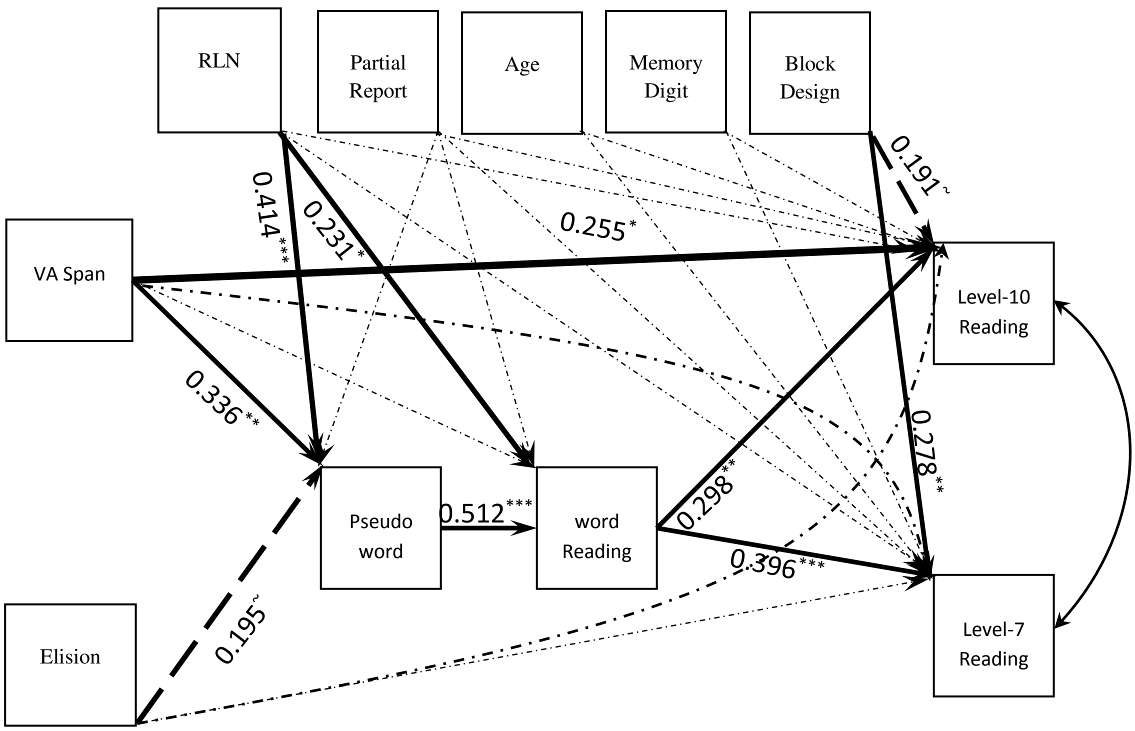

Figure 2. Path diagram for the fitted Model with only significant paths (standardized coefficients) displayed as bold solid lines. Insignificant paths are shown in dashed lines. This figure shows Global VA span has a direct effect on Level-10 reading comprehension, and also has an indirect effect to both levels of reading comprehension via phonemic decoding and word reading skills. Most of the variables controlled for do not have a significant effect on reading comprehension except for block design and rapid letter naming. The labels in Figure 2 are the measurements that correspond to the skills labelled in Figure 1.

* ρ <= 0.05
** ρ <= 0.01
*** ρ <= 0.001
~ ρ <= 0.06