



## Developmental changes in the visual span for reading

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### Abstract

The visual span for reading refers to the range of letters, formatted as in text, that can be recognized reliably without moving the eyes. It is likely that the size of the visual span is determined primarily by characteristics of early visual processing. It has been hypothesized that the size of the visual span imposes a fundamental limit on reading speed [Legge, G. E., Mansfield, J. S., & Chung, S. T. L. (2001). Psychophysics of reading. XX. Linking letter recognition to reading speed in central and peripheral vision. *Vision Research*, 41, 725–734]. The goal of the present study was to investigate developmental changes in the size of the visual span in school-age children and the potential impact of these changes on children's reading speed. The study design included groups of 10 children in 3rd, 5th, and 7th grade, and 10 adults. Visual span profiles were measured by asking participants to recognize letters in trigrams (random strings of three letters) flashed for 100 ms at varying letter positions left and right of the fixation point. Two print sizes (0.25° and 1.0°) were used. Over a block of trials, a profile was built up showing letter recognition accuracy (% correct) versus letter position. The area under this profile was defined to be the size of the visual span. Reading speed was measured in two ways: with Rapid Serial Visual Presentation (RSVP) and with short blocks of text (termed Flashcard presentation). Consistent with our prediction, we found that the size of the visual span increased linearly with grade level and it was significantly correlated with reading speed for both presentation methods. Regression analysis using the size of the visual span as a predictor indicated that 34–52% of variability in reading speeds can be accounted for by the size of the visual span. These findings are consistent with a significant role of early visual processing in the development of reading skills. © 2007 Elsevier Ltd. All rights reserved.

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### 1. Introduction

Children's reading speed increases throughout the school years. According to Carver (1990), from grade 2 to college, the average reading rate increases about 14 standard-length words per minute<sup>1</sup> each year. Learning to read involves becoming proficient in phonological, linguistic and perceptual components of reading (Aghababian & Nazir, 2000). By age 7, normally sighted children reach

nearly adult levels of visual acuity (Dowdeswell, Slater, Broomhall, & Tripp, 1995). By first grade, typically 6 years of age, most of them know the alphabet. Nevertheless, reading speed takes a long time to reach adult levels.

Many studies have addressed potential explanations for developmental changes in reading skills. Because it is often assumed that visual development is complete by the beginning of grade school, most studies have focused on the role of phonological or linguistic skills in learning to read (e.g., Adams, 1990; Goswami & Bryant, 1990; Muter, Hulme, Snowling, & Taylor, 1997). Consistent with this focus, one widely accepted view is that linguistic skills are predictive of reading performance and serve as the locus of differences in reading ability. According to this view, skilled and less skilled readers extract the same amount of visual information during the time course of an eye fixation, but skilled

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<sup>1</sup> Carver (1977) defined six characters in text (including spaces and punctuation) as one "standard-length word." Measuring reading speed in standard-length words per minute is a character-based metric. Carver (1990) argued for the advantage of this metric over the common "words per minute" metric for measuring reading speed.

readers have more rapid access to letter name codes (e.g., Jackson & McClelland, 1979; Neuhaus, Foorman, Francis, & Carlson, 2001), make better use of linguistic structure to augment the visual information (Smith, 1971), or process the information more efficiently through a memory system (Morrison, Giordani, & Nagy, 1977) (as cited in Mason, 1980, p. 97). It is further argued that inefficient eye movement control observed in less skilled readers is a reflection of linguistic processing difficulty (Rayner, 1986, 1998) rather than a symptom of perceptual difference per se.

Stanovich and colleagues have critiqued the general view that differences in reading skill are primarily due to top-down linguistic influences. See Stanovich (2000, Ch. 3) for a review. Stanovich (2000) has summarized findings showing that recognition time for isolated words is highly correlated with individual differences in reading fluency. This work has focused interest on the speed of perceptual processing, rather than top-down cognitive or linguistic influences, in accounting for individual differences in normal reading performance. The differences in word-recognition time among normally sighted subjects could be due to differences in the transformation from visual to phonological representations of words, or to differences at an earlier, purely visual, level of representation. In short, it remains plausible that individual differences in reading skill, and also the development of reading skill, are at least partially due to differences in visual processing.

Five lines of evidence implicate vision as a factor influencing reading development. (1) The characteristics of children's eye movements differ from those of adults, showing smaller and less precise saccades than adults (Kowler & Martins, 1985). (2) Mason and Katz (1976) found that good and poor readers among 6th-grade children differed in their ability to identify the relative spatial position of letters. Farkas and Smothergill (1979) also found that performance on a position encoding task improved with grade level<sup>2</sup> in children in 1st, 3rd and 5th grade. (3) It was found that children's reading ability was associated with orientation errors in letter recognition such as confusing *d* and *b*, or *p* and *q* stressing the role of visual-orthographic skill in reading (e.g., Cairns & Setward, 1970; Davidson, 1934, 1935; Terepocki, Kruk, & Willows, 2002). (4) More direct evidence for the involvement of visual processing in children's reading development was obtained by O'Brien, Mansfield, and Legge (2005). They observed that the critical print size for reading decreases with increasing age. (Critical print size refers to the smallest print size at which fast, fluent reading is possible.) A similar character-size dependency of reading performance was also observed by Hughes and Wilkins (2000) and Cornelissen, Bradley, Fowler, and Stein (1991). (5) Letter recognition, a necessary

component process in word recognition (e.g., Pelli, Farell, & Moore, 2003), is known to be degraded by interference from neighboring letters (Bouma, 1973). This crowding effect decreases with age in school-age children (Bondarko & Semenov, 2005) and is significantly worse in children with developmental dyslexia compared with normal readers (Spinelli, De Luca, Judica, & Zoccolotti, 2002). It should also be noted that there is a related debate in the literature over the role of visual factors in dyslexia, especially the impact of visual processing in the magnocellular pathway. For competing views, see the reviews by Stein and Walsh (1997) and Skottun (2000a,b).

Collectively, the empirical findings briefly summarized above suggest a role for early visual processing in the development of reading skills. The question of whether there is an early perceptual locus for reading differences is an important one to resolve both for a better understanding of the reading process and for remediation purposes. In the present paper, we ask whether vision plays a role in explaining the known developmental changes in reading speed.

Legge, Mansfield, and Chung (2001) studied the relationship between reading speed and letter recognition. They proposed that the size of the visual span<sup>3</sup>—the range of letters, formatted as in text, that can be recognized reliably without moving the eyes—covaries with reading speed. They also proposed that shrinkage of the visual span may play an important role in explaining reduced reading speed in low vision. Work in our lab has shown that for adults with normal vision, manipulation of text contrast and print size (Legge, Cheung, Yu, Chung, Lee, & Owens, 2007), character spacing (Yu, Cheung, Legge, & Chung, 2007), and retinal eccentricity (Legge et al., 2001) produce highly correlated changes in reading speed and the size of the visual span. Pelli, Tillman, Freeman, Su, Berger, and Majaj (in press) have recently shown that a similar concept, which they term “uncrowded span,” is directly linked to reading speed. The influential role of the size of the visual span in reading speed was also demonstrated in a computational model called “Mr. Chips”, which uses the size of the visual span as a key parameter (Legge, Hooven, Klitz, Mansfield, & Tjan, 2002; Legge, Klitz, & Tjan, 1997). These empirical and theoretical findings provide growing evidence for a linkage between reading speed and the size of the visual span.

We measured the visual spans of children at three grade levels to examine developmental changes in early visual processing. The size of the visual span was measured using a trigram<sup>4</sup> (random strings of three letters) identification

<sup>3</sup> The term ‘visual span’ was introduced by O'Regan (1990, 1991) and O'Regan et al. (1983). He defined the visual span as the region around the point of fixation within which characters of a given size can be resolved. Empirical studies have shown that normally sighted adults have a visual span of 7–11 letters. For a review, see Legge (2007, Ch. 3).

<sup>4</sup> Trigrams were used rather than isolated letters because of their closer approximation to English text. Text contains strings of letters. Most letter recognition in text involves characters flanked on the left, right or both sides.

<sup>2</sup> In this article, school grade levels refer to the American system. The correspondence between grade level and age is as follows: 1st grade (6–7 yrs), 2nd grade (7–8 yrs), 3rd grade (8–9 yrs), 4th grade (9–10 yrs), 5th grade (10–11 yrs), 6th grade (11–12 yrs), 7th grade (12–13 yrs), and 8th grade (13–14 yrs).

task (Legge et al., 2001). In this method, participants are asked to recognize letters in trigrams flashed briefly at varying letter positions left and right of the fixation point as shown in the top panel of Fig. 1. Over a block of trials, a visual-span profile is built up—a plot of letter recognition accuracy (% correct) as a function of letter position left and right of fixation—as shown in the bottom panel of Fig. 1. These profiles quantify the letter information available for reading. The method of measurement means that the profiles are largely unaffected by oculomotor factors and top-down contextual factors. Trigram identification captures two major properties of visual processing required for reading: letter identification and encoding of the relative positions of letters.

We distinguish between the concept of the visual span and the concept of the perceptual span (McConkie & Rayner, 1975). Operationally, the perceptual span refers to the region of visual field that influences eye movements and fixation times in reading. The size of the perceptual span is typically measured using either *the moving window technique* (McConkie & Rayner, 1975) or *moving mask technique* (Rayner & Bertera, 1979). The perceptual span is estimated to extend about 15 characters to the right of fixation and four characters to the left of fixation. Rayner (1986) argued that the perceptual span reflects readers' linguistic processing or overall cognitive processing rather than visual processing per se. On the other hand, the visual span is relatively immune to oculomotor and top-down contextual influences and is likely to be primarily determined by the characteristics of front-end visual processing.

Rayner (1986) measured the size of the perceptual span and characteristics of saccades and fixation times in children in second, fourth and sixth grades, and in adults. He found an increase in the size of the perceptual span

and a decrease in fixation times with age. These oculomotor changes could be due to maturation in eye movement control or to secondary factors influencing eye movement control (either bottom-up visual factors, or top-down cognitive factors). Rayner (1986) attributed the developmental changes in eye movements to top-down cognitive factors because the size of the perceptual span and fixation duration were found to be dependent on the text difficulty. For example, he found that when children in fourth grade were given age appropriate text material, their fixation times and the size of the perceptual span became close to those of adults.

To confirm that oculomotor maturation is not the major source of developmental changes in reading speed, we tested our participants with two types of reading displays. First, Rapid Serial Visual Presentation (RSVP) reading minimizes the need for intra-word reading saccades and removes the reader's control of fixation times. Second, in our Flashcard method, participants read short blocks of text requiring normal reading eye movements. If maturation of eye-movement control is an important contributor to the development of reading speed, we would expect to observe a greater developmental effect in flashcard reading compared with RSVP reading. To the extent that growth in the size of the visual span is a contributor to the development of reading speed, we would expect to find a similar positive correlation with reading speed for both types of displays.

We also asked whether letter size affects the size of the visual span. Print size in children's books is usually larger than for adult books. The typical print size for children's books ranges from 5 to 10 mm in  $x$ -height, equivalent to  $0.72$ – $1.43^\circ$  at a viewing distance of 40 cm (Hughes & Wilkins, 2002). Hughes and Wilkins (2000) found that the reading speed of children aged 5–7 years decreased as the text size decreased below this range while older children aged 8–11 years were less dependent on letter size. O'Brien et al. (2005) reported that the critical print size (CPS) decreases with increasing age in school-age children, showing that younger children need a larger print size in order to reach their maximum reading speed than older children. The critical print size (CPS) for adults is close to  $0.2^\circ$  (Legge, Pelli, Rubin, & Schleske, 1985; Mansfield, Legge, & Bane, 1996). It has also been observed that the size of the visual span shows the same dependence on character size as reading speed (Legge et al., 2007). It is possible that the use of larger print in children's books reflects the need for larger print size to maximize reading speed. In this study, we used two letter sizes— $0.25^\circ$ , which is slightly above the CPS of adults and  $1^\circ$ , which is substantially larger than the CPS. Our goal was to assess the impact of this difference on the size of the visual span and reading speed for children.

We summarize the goals of this study as follows:

First, we hypothesize that developmental changes in the size of the visual span play a role in the developmental increase in reading speed. To test this hypothesis, we mea-

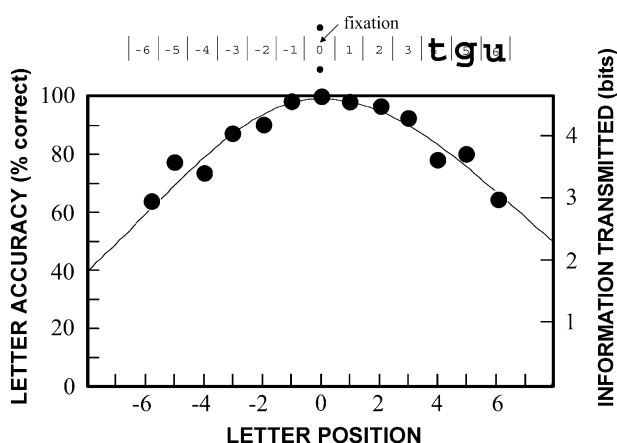


Fig. 1. Visual span profile. Top: Illustrates that trials consist of the presentation of trigrams, random strings of three letters, at specified letter positions left and right of fixation. Bottom: Example of a visual-span profile, in which letter recognition accuracy (% correct) is plotted as a function of letter position for data accumulated across a block of trials. The right vertical scale shows the transformation from accuracy to information transmitted in bits (see Section 2 for more details). The size of the visual span is the sum of the information transmitted in bits across the letter positions.

sured the size of the visual span and reading speed for children at three grade levels (3rd, 5th and 7th) and for young adults. A testable prediction of the hypothesis is that the visual span increases in size with age and is positively correlated with reading speed.

Secondary goals were to (1) examine the effect of letter size on the development of the visual span and (2) to assess the influence of oculomotor control with a comparison of RSVP and flashcard reading.

## 2. Methods

### 2.1. Participants

Groups of 10 children in 3rd, 5th, and 7th grade and 10 adults (college students) participated in this study. The children were recruited from the Minneapolis public schools. They were all screened to have normal vision and to be native English speakers. Students with reading disabilities, speech problems or cognitive deficits were excluded. Cooperating teachers at the schools were asked to select students in each grade level to approximately match students for IQ and academic standing across grade levels. Ten college students were recruited from the University of Minnesota with the same criteria. For each participant, visual acuity and reading acuity were assessed with the Lighthouse Near Acuity Test and MNREAD chart, respectively. Proper refractive correction for the viewing distance was made. All participants were paid \$10.00 per hour. Informed consent was obtained from parents or the legal guardian in addition to the assent of children in accordance with procedures approved by the internal review board of the University of Minnesota. The mean age, visual acuity, and gender ratio for participants in the different grades are provided in Table 1.

### 2.2. Stimuli

Trigrams, random strings of three letters, were used to measure visual-span profiles. Letters were drawn from the 26 lowercase letters of the English alphabet (repeats were possible). By chance some of the trigrams are three-letter English words (e.g. dog, fog) which might be easier to recognize. However, the chance of getting a word trigram is less than 2% which is not likely to have much influence on the overall letter recognition accuracy (c.f. Legge et al., 2001).

All letters were rendered in a lower case Courier bold font (Apple Mac)—a serif font with fixed width and normal spacing. The letters were dark on a white background (84 cd/m<sup>2</sup>) with a contrast of about 95%. Letter size is defined as the visual angle subtended by the font's *x*-height. The *x*-height of 0.25° and 1° character size corresponded to 6 pixels and 24 pixels. The viewing distance for all testing was 40 cm. The same font was used for measuring reading speeds (see below).

The stimuli were generated and controlled using Matlab (version 5.2.1) and Psychophysics Toolbox extensions (Brainard, 1997; Pelli, 1997). They were rendered on a SONY Trinitron color graphic display (model: GDM-FW900; refresh rate: 76 Hz; resolution: 1600 × 1024). The display was controlled by a Power Mac G4 computer (model: M8570).

Table 1  
Mean age, visual acuity and gender ratio for participants

	3rd	5th	7th	Adult
Mean age (years)	9.14 (±0.47)*	11.09 (±0.5)	13.05 (±0.51)	21.30 (±3.20)
Near visual acuity (logMAR)	−0.06	−0.1	−0.05	−0.1
Gender ratio (male:female)	5:5	4:6	6:4	4:6

\* Note. The numbers in parenthesis are standard deviations.

Oral reading speed was measured with two methods—Rapid Serial Visual Presentation (RSVP) and a static text display (Flashcard). The pool of test material consisted of 187 sentences in the original MNREAD format developed for testing reading speed by Legge, Ross, Luebker, and LaMay (1989). All the sentences were 56 characters in length. In the Flashcard presentation, the sentences were formatted into four lines of 14 characters (Fig. 2b).

The mean word length was 3.7 letters and 93% of the 1581 unique words occur in the 2000 most frequent words based on *The Educator's Word Frequency Guide* (Zeno, Ivens, Millard, & Duvvuri, 1995). Mean difficulty of the sentences in the pool was 4.77 (Gunning's Fog Index), and 1.34 (Flesh-Kincaid Index). According to Carver's (1976) formula<sup>5</sup>, the mean difficulty level is below 2nd grade level. Allowing for differences in these metrics, the difficulty of the sentences is roughly 2nd to 4th grade level. Sample sentences are presented in Fig. 2c. We divided the sentence pool into three sub-pools, so that there were separate, non-overlapping sets of sentences for RSVP, Flashcard, and practice. Sentences were selected randomly without replacement, so that no subject saw the same sentence more than once during testing.

### 2.3. Measuring visual-span profiles

Visual-span profiles were measured using a letter recognition task, as described in Section 1. Trigrams were presented with their middle letter at 11 letter positions, including 0 (the letter position at fixation) and from 1 to 5 letter widths left and right of the 0 position. Trigram position was indexed by the middle letter of the trigram. For instance, a trigram *abc* at the position +3 had the *b* located in position 3 to the right of the 0 letter position, and a trigram at position −3 had its middle letter three letter positions to the left.

Each of the 11 trigram positions was tested 10 times, in a random order, within a block of 110 trials. The task of the participant was to report the three letters from left to right. A letter was scored as being identified correctly only if its order within the trigram was also correct. Feedback was not provided to the participants about whether or not their responses were correct.

Participants were instructed to fixate between two vertically separated fixation points (Fig. 1) on the computer screen during trials. The experimenter visually observed participants to confirm that these instructions were being followed. Since there was no way of predicting on which side of fixation the trigram would appear, and the exposure time was too brief to permit useful eye movements, the participants understood that there was no advantage to deviate from the intended fixation. All participants had practice trials in the trigram test, RSVP test and Flashcard test prior to data collection. Participants were verbally encouraged to fixate carefully between the dots at the beginning of a trial.

Proportion correct recognition was measured at each of the letter slots and combined across the trigram trials in which the letter slot was occupied by the outer (the furthest letter from fixation), middle, or inner (the one closest to fixation) letter of a trigram. This means that although trigrams were centered at a given position only 10 times in a block, data from that position were based on 30 trials. As described in Section 1, a visual span profile consists of percent correct letter recognition as a function of position left and right of fixation. These profiles are fit with "split Gaussians", that is, Gaussian curves that are characterized with amplitude (the peak value at letter position 0), and the left and right standard deviations (the breadth of the curve). These profiles usually peak at the midline and decline in the left and right visual fields. The profiles are often slightly broader on the right of the peak (Legge et al., 2001).

<sup>5</sup> We estimated the grade level from Carver (1976) who expressed the relationship between characters per word (cpw) and difficulty level ( $D_L$ ). According to his formula, the number of characters per word for 1st grade difficulty is approximately 5 cpw including a trailing space after each word, which is slightly above the number of characters per word (4.7 cpw including a trailing space after each word) we used for our reading tasks.



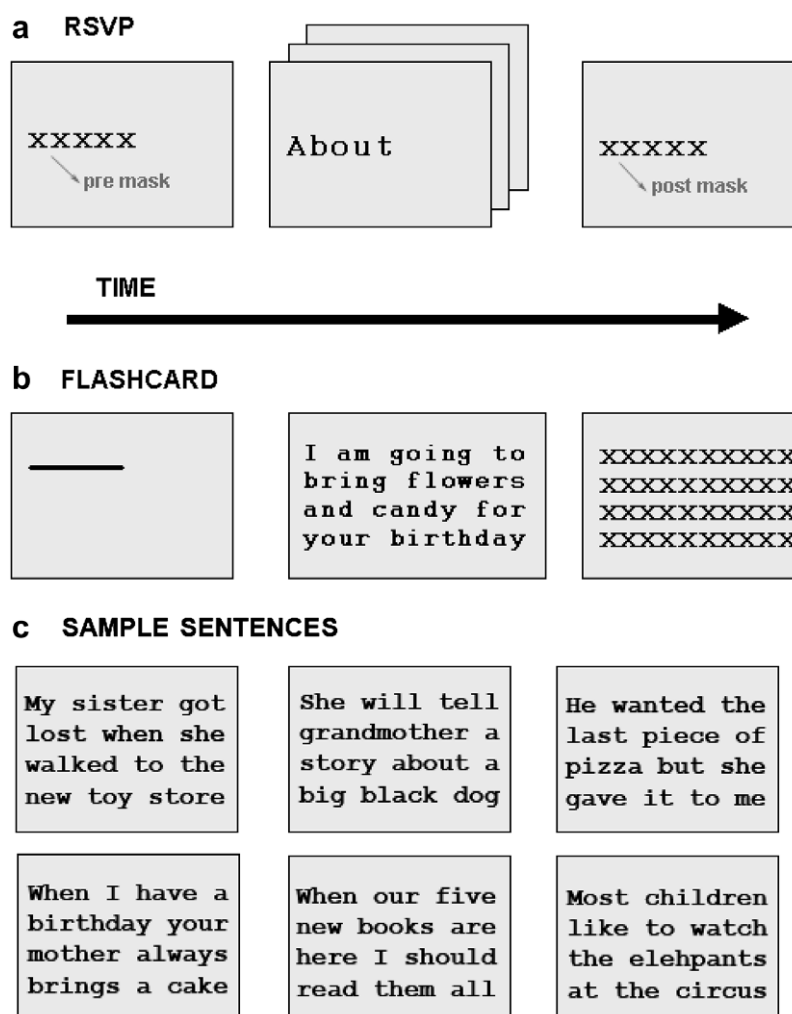


Fig. 2. Schematic Diagram of RSVP (a) and Flashcard (b) reading speed tasks and Sample sentences (c).

As described in Section 1 and illustrated in Fig. 1 (i.e., the right vertical scale), percent correct letter recognition can be linearly transformed to information transmitted in bits. The information values range from 0 bits for chance accuracy of 3.8% correct (the probability of correctly guessing one of 26 letters) to 4.7 bits for 100% accuracy (Legge et al., 2001)<sup>6</sup>. The size of the visual span is quantified by summing across the information transmitted in each slot (similar to computing the area under the visual-span profile). Lower and narrower visual span profiles transmit fewer bits of information. In the Results, the size of the visual span will be quantified in units of bits of information transmitted.

Visual-span profiles were measured for each participant at two letter sizes (0.25° and 1°). In both cases, the stimulus exposure time was 100 ms. The order of the two conditions was interleaved both within participants and across participants (e.g. participant A started with 1° letter size while participant B started with 0.25° letter size, and so on).

#### 2.4. Measuring reading speed

Oral reading speed was measured with two testing methods: Rapid Serial Visual Presentation (RSVP) and static text (Flashcard method). For both testing conditions, the method of constant stimuli was used to present sentences at five exposure times in logarithmically spaced steps,

spanning  $\sim 0.7$  log units. For both reading speed tasks, the two letter size conditions were interleaved. The testing session was preceded by a practice session. During this session, the range of exposure times for each participant was chosen in order to make sure that at least 80% correct response (percent of words correct in a sentence) was obtained at the longest exposure time.

For RSVP, the sentences were presented sequentially one word at a time at the same screen location (i.e., the first letter of each word occurred at the same screen location). There was no blank frame (inter-stimulus interval) between words. Each sentence was preceded and followed by strings of x's as shown in Fig. 2a. In the Flashcard reading test, an entire sentence was presented on the screen as shown in Fig. 2b.

For both tasks, participants initiated each trial by pressing a key. They were instructed to read the sentences aloud as quickly and accurately as possible. Participants were allowed to complete their verbal response at their own speed, not under time pressure. A word was scored as correct, even if given out of order, e.g., a correction at the end of a sentence, the number of words read correctly per sentence was recorded. Five sentences were tested for each exposure time and percent correct word recognition was computed at each exposure time.

Psychometric functions, percent correct versus log RSVP or log Flashcard exposure times, were created by fitting these data with cumulative Gaussian functions (Wichmann & Hill, 2001a) as shown in Fig. 3. The four panels represent four sets of data from RSVP and Flashcard tasks at two letter sizes. Five data points in each panel represent percent words correct in a sentence for RSVP and for Flashcard. The threshold exposure

<sup>6</sup> Percent correct letter recognition was converted to bits of information using letter-confusion matrices by Beckmann (1998).

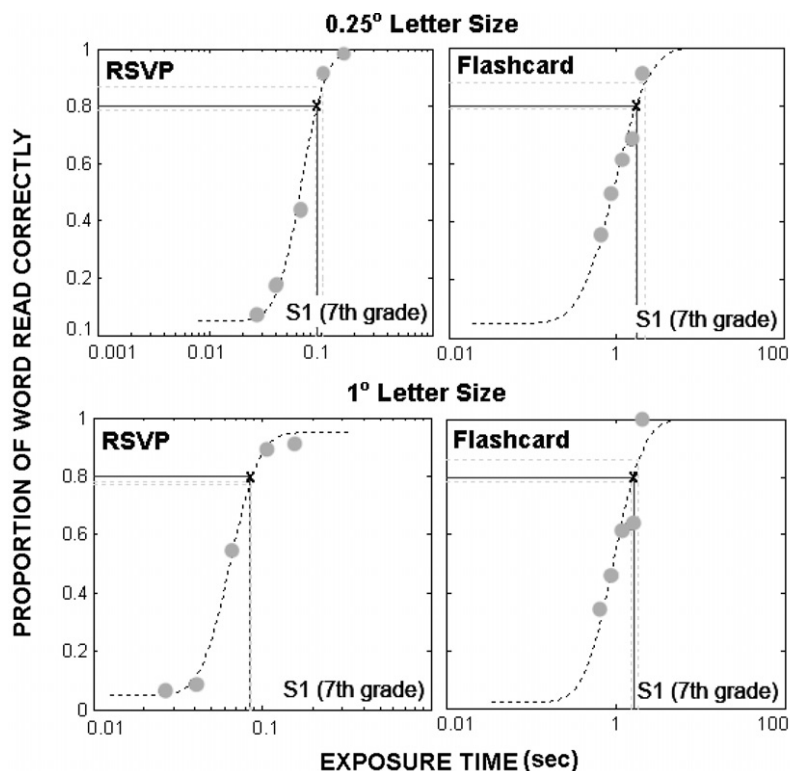


Fig. 3. Proportion of words read correctly is plotted as a function of exposure time in sec per word for RSVP and exposure time in sec per sentence for Flashcards (Participant S1, 7th grader). The top two panels show RSVP and Flashcard data for letter size  $0.25^\circ$ . The bottom two panels show RSVP and Flashcard data for letter size  $1^\circ$ . Each set of data was fit with a cumulative Gaussian function. From each psychometric function, the threshold exposure time was defined as the exposure time yielding 80% of words read correctly.

time, for words of a given length was based on the 80% correct point on the psychometric function. For example, in RSVP, if an exposure time of 200 msec per word yielded 80% correct, the reading rate was 5 words per second, equals to 300 wpm. For Flashcard, if the exposure time was 2 sec and the participant read 8 words correctly out of ten, the corresponding reading speed was 4 words per second, equals to 240 wpm.

### 3. Results

Three dependent variables were measured: the size of the visual span, RSVP reading speed and flashcard reading speed. We conducted one ANOVA test for each measure. The grade level (3rd, 5th, 7th, and Adult) was treated as a categorical variable rather than numerical variable for the statistical analysis.

A 4 (grade)  $\times$  2 (letter size) repeated measures ANOVA with grade as a between-subject factor and letter size as a within-subject factor was tested on the size of the visual span. There was a significant main effect of grade level on the size of the visual span ( $F_{(3,36)} = 9.54, p < 0.01$ ). There was a significant interaction effect between grade level and letter size ( $F_{(3,36)} = 3.46, p = 0.02$ ). But no significant main effect of letter size on the size of the visual span was found.

A 4 (grade)  $\times$  2 (letter size) repeated measures ANOVA with grade as a between-subject factor and letter size as a within-subject factor was tested on RSVP and flashcard reading speeds separately. There was a main effect of grade

level on RSVP reading speed ( $F_{(3,36)} = 7.80, p < 0.01$ ) and Flashcard reading speed ( $F_{(3,36)} = 9.35, p < 0.01$ ). No significant letter size effects on reading speed were found.

#### 3.1. The effects of grade level on the size of the visual span and reading speed

The 4  $\times$  2 repeated measure ANOVA test showed that there was a significant main effect of grade on the size of the visual span ( $\eta^2 = 0.44, p < 0.01$ ). A pairwise contrast test also showed that there were significant differences in the size of the visual span among all pairs of grades except between 3rd and 5th grades. Fig. 4 summarizes the average visual-span size for each grade group collapsed across two letter sizes. These results show that the visual span grows in size from 3rd grade (mean =  $34.28 \pm 1.17$  bits) to adults (mean =  $41.66 \pm 0.87$  bits). The effect size (using Cohen's  $d$ ) of the difference in the size of the visual span between 3rd grade and adults equals to 2.28.

We also found that there was a significant main effect of grade level on both RSVP ( $\eta^2 = 0.39, p < 0.01$ ) and Flashcard ( $\eta^2 = 0.44, p < 0.01$ ) reading speeds. Fig. 5 shows RSVP (left panel) and Flashcard (right panel) reading speeds (wpm) as a function of grade level. Each data point represents the average reading speed for 10 participants. The error bar represents  $\pm 1$  standard error of the mean.

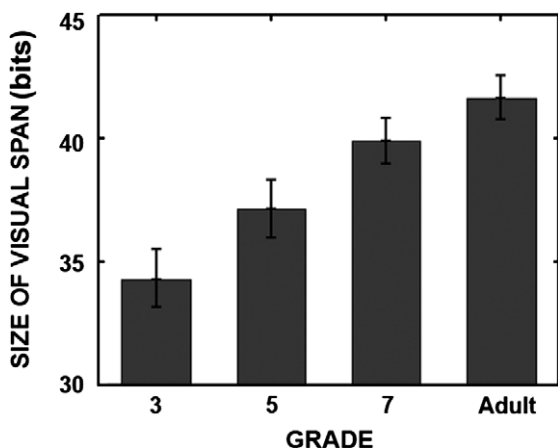


Fig. 4. The size of the visual span for students in three grades and for adults. Each bar indicates the average visual-span size for 10 participants collapsed across the two letter sizes. The error bars represent  $\pm 1$  standard error of the mean.

Open circles in both panels represent reading speeds for  $1^\circ$  letters, and the closed circles for  $0.25^\circ$  letters.

As shown in Fig. 5, there was a linear increase in both RSVP and flashcard reading speeds with grade level. As expected from prior research, RSVP reading speed was faster than Flashcard reading speed for all groups by an average factor of 1.58, which is fairly consistent with the results (i.e. a factor of 1.44) for a similar comparison by Yu et al. (2007). The growth in RSVP reading speed across grades exceeds the growth in flashcard reading speed, confirming the view that maturation of the oculomotor system is not a major factor associated with the growth in children's reading speed.

The increment in flashcard reading speed per grade was consistent with earlier studies of page reading speed (Carver, 1990; Taylor, 1965; Tressoldi, Stella, & Faggella, 2001). Carver (1990) estimated that the growth in reading speed was 14 standard-length words per minute per grade

level (where one standard-length word is equivalent to 6 characters). The average increment for Flashcard reading speed in our study was approximately 18 words per minute each year and its transformed value into Carver's metric is 14 wpm, equal to Carver's estimate.

### 3.2. Relationship between the size of the visual span and reading speed

Flashcard and RSVP reading speeds are plotted against the size of the visual span for our 40 participants in Figs. 6 and 7, respectively. The closed circles, open circles, closed squares, and open squares show data for 3rd, 5th, 7th grade, and adults, respectively. The best-fitting lines for predicting reading speed from the size of the visual span are also shown.

There were significant correlations between the size of the visual span and Flashcard reading speed ( $r = 0.72$ ,  $p < 0.01$ ), and RSVP reading speed ( $r = 0.58$ ,  $p = 0.01$ ).

From the regression model for flashcard reading (Fig. 6), 52% of the variability of the reading speed can be accounted for by the size of the visual span ( $r^2 = 0.52$ ,  $p < 0.01$ ). The slope of the regression line indicates that an increase in the size of the visual span by 1 bit brings about an increase in reading speed by 22 wpm. The effect size (Cohen's  $d$ ) is 2.29 for the difference in flashcard reading speed between 3rd graders and adults. Similarly, from the regression model for RSVP reading (Fig. 7), 33% of the variability of the reading speed can be accounted for by the size of the visual span ( $r^2 = 0.34$ ,  $p < 0.01$ ). The slope of the regression line indicates that an increase in the size of the visual span by 1 bit brings about an increase in reading speed by 28 wpm. The effect size (Cohen's  $d$ ) is once again 2.29 for the difference in RSVP reading speed between 3rd graders and adults.

As described in Section 2, reading speed was derived from the stimulus exposure time yielding 80% correct word

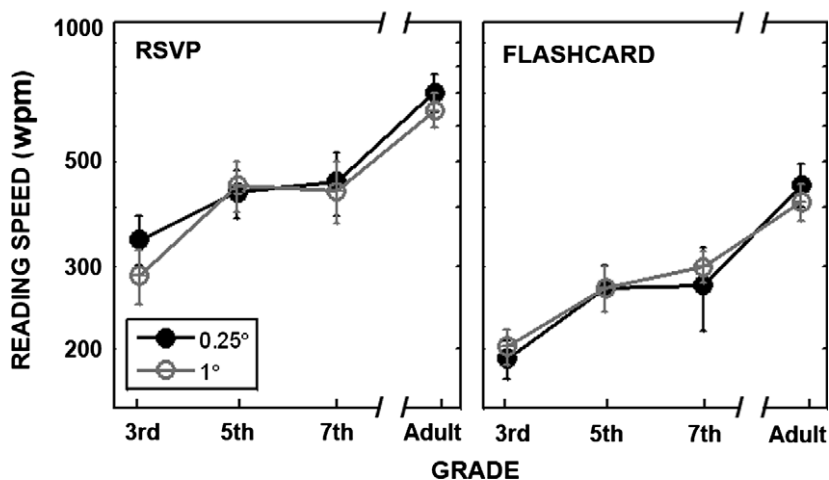


Fig. 5. Reading speed (wpm) as a function of grade level for two letter sizes. Each data point represents the average reading speed for 10 participants. Each error bar represents  $\pm 1$  standard error of the mean. Open circles in both panels represent reading speeds for  $1^\circ$  letters, and the closed circles for  $0.25^\circ$  letters. Left Panel: RSVP. Right Panel: Flashcard reading speed.

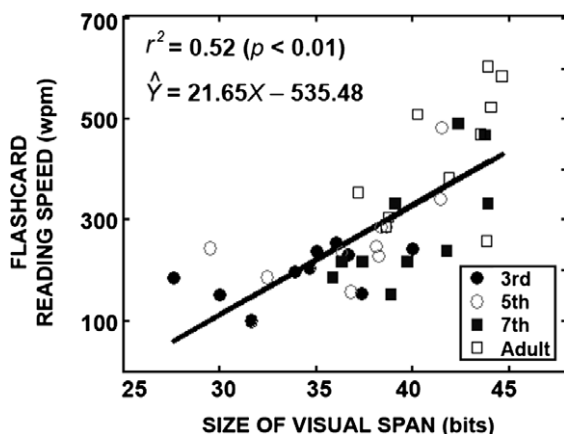


Fig. 6. Flashcard reading speed (wpm) as a function of the size of the visual span. The solid line represents a regression line. Each data point represents the average across two letter sizes for one participant. Closed circles, open circles, closed squares, and open squares represent data for 3rd, 5th, 7th grade, and adults respectively.

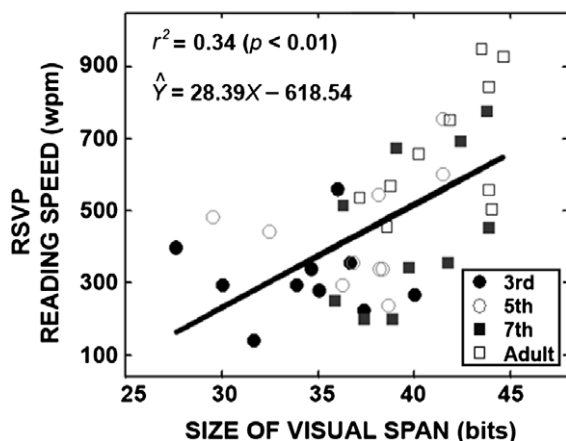


Fig. 7. RSVP reading speed (wpm) as a function of the size of the visual span. The solid line represents a regression line. Each data point represents the average across two letter sizes of one participant. Closed circles, open circles, closed squares, and open squares represent data for 3rd, 5th, 7th grade, and adults respectively.

recognition. To determine if the results were sensitive to this criterion, we reanalyzed the data with 70% and 90% criteria for defining reading speed. We found that the relationship between reading speed and the size of the visual span was not criterion dependent – correlations between size of the visual span and reading speed remained approximately the same across all three criteria (less than 0.01 differences in correlation coefficients).

### 3.3. The effects of letter size on the visual span and reading speed

We did not find a significant main effect of letter size on either the visual span or reading speeds in children. Contrary to the possibility raised in Section 1, it does not appear that the use of larger print size in children's books

can be explained in terms of optimizing the size of the visual span at least for children aged 8–13 years old.

While children in all three grade levels showed no dependence of letter size on the size of the visual span, adults showed slightly larger visual spans for 0.25° letters than for 1° letters (~3 bits). Legge et al. (2007) studied the effect of character size on the size of the visual span for a group of five young adults. They did not find any significant difference in the size of the visual span between 0.25° and 1°. We are unsure of the reason for the small discrepancy in the two studies.

## 4. Discussion

### 4.1. Relationship between reading speed and the size of the visual span

It is obvious that visual processing is critical to print reading. It is not so obvious that individual differences in reading speed are linked to differences in visual processing nor that developmental changes in reading speed are influenced by visual factors. We have taken the theoretical position that front-end visual processing influences letter recognition which in turn influences reading speed. We have measured letter recognition in the form of visual-span profiles. The shape and size of these profiles are largely immune to top-down contextual factors and to oculomotor factors, and represent the bottom-up sensory information available to letter recognition and reading. The size of these profiles has been previously linked empirically and theoretically to reading speed (Legge et al., 2001, 2007). More specifically, it is hypothesized that the size of the visual span is an important determinant of reading speed.

As reviewed in Section 1, it is known that children's reading speed gradually increases throughout the school years (cf., Carver, 1990). The principal goal of our study was to determine whether visual development has an impact on this improvement in reading speed. We addressed this question by measuring changes in the size of the visual span across grade levels. Our hypothesis was that the size of the visual span would increase with grade level, and exhibit a correlation with reading speed.

These predictions were confirmed by our results. We found that there was a developmental growth in the size of the visual span from 3rd grade to adulthood paralleling growth in reading speed. A statistically significant 34–52% of the variance in reading speed could be accounted for by the size of the visual span.

Why does a larger visual span facilitate faster reading? For eye-movement mediated reading of lines of text on a page or screen (such as the flashcards in the present study), a larger visual span means that more letters can be recognized accurately on each fixation. With a larger visual span, longer words might be recognized on one fixation, or more letters of an adjacent word might be recognized if the fixated word is short (parafoveal preview). The effects of changing the size of the visual span were explored using



an ideal-observer model, called Mr. Chips, by Legge et al. (1997). Because a larger visual span means that more letters are recognized, the reader is able to make larger saccades; the greater mean saccade length facilitates faster reading. In the case of RSVP reading, there is no need for intra-word saccades or parafoveal preview of the leading letters of the next word. Only one word is visible at a time. In this case, we might speculate that the visual span need only be large enough to accommodate mean word length of the text (3.94 letters in the present study) or possibly the longest word in the text (8 letters in our text). If so, we might expect a weaker effect of visual-span size on RSVP reading speed, and possibly a ceiling once the visual span exceeded some critical value. These effects are not evident in the present data. Growth of the visual span manifests as both an increase in the breadth of visual-span profiles and also an increase in the height of the profiles, i.e., increasing letter-recognition accuracy in the central portion of the profile. The increased height of the profile could contribute to faster and more accurate recognition, even of relatively short strings. In other words, the graded form of the visual-span profile, and its potential growth in both height and breadth, can contribute to faster reading for both flashcard and RSVP text.

We recognize that our results are correlational in nature. It is possible that independent factors could drive the developmental changes in reading speed and size of the visual span. Although a causal link between the size of the visual span and reading speed remains to be proven, stronger evidence for a causal link has been provided by Legge et al. (2007). These authors have amassed convergent data from several experiments on adults showing that the size of the visual span and reading speed vary in a highly correlated way in response to changes in stimulus parameters such as contrast and character size. For example, it is known that the dependence of reading speed on character size exhibits a nonmonotonic relationship in which reading speed has a maximum value for a range of intermediate character sizes, and decreases for larger and smaller character sizes. Legge et al. (2007) showed that the size of the visual span has the same nonmonotonic dependence on character size.

#### 4.2. Sensory factors affecting the size of the visual span

What sensory factors might contribute to developmental changes in the size of the visual span? In Section 1, we mentioned three candidate factors—errors in the relative position of letters in strings, orientation errors such as confusing *b* with *d*, and effects of crowding. We briefly comment on additional analyses of our visual-span data to address the roles of these factors.

Errors in relative spatial position (e.g., reporting *bqx* when the stimulus was *qbx*), sometimes termed mislocation errors, were evaluated by scoring trigram letter recognition in two ways; by demanding correct relative position for a letter to be correct, or by the more lenient criterion of scor-

ing a letter correct if reported anywhere in the trigram string. The difference in percent correct by these two scoring methods is a measure of the rate of mislocation errors. An one-way ANOVA with grade (3rd, 5th, 7th, and Adult) as a between-subject factor revealed a significant main effect of grade on the rate of mislocation errors ( $F_{(3,36)} = 4.55, p < 0.01$ ). The rate of mislocation errors increased with decreasing grade level (mean error rate for 3rd grade =  $8.43 \pm 1.1\%$  vs. the mean error rate for adults =  $4.25 \pm 0.5\%$ ). Mislocation errors could be cognitive in origin, resulting from verbal-reporting mistakes, or visual in origin, resulting from imprecise coding of visual position. We think the latter is more likely because we found that the rate of mislocation errors was dependent on visual-field location, increasing at greater distances from fixation. This dependency of mislocation errors on letter position was consistent across all age groups.

We assessed orientation errors by measuring *b* and *d* confusions, and also *p* and *q* confusions. Orientation errors are defined when *b* (or *p*) is reported instead of *d* (or *q*) and vice versa. The number of incorrect responses out of the total number of occurrence of *b*, *p*, *d*, and *q* is a measure of the rate of orientation errors. An one-way ANOVA with grade as a between-subject factor revealed a significant main effect of grade on the rate of orientation errors ( $F_{(3,36)} = 4.98, p < 0.01$ ). Orientation errors decreased with increasing grade level (mean error rate for 3rd grade =  $5.85 \pm 0.40\%$  vs. mean error rate for adults =  $3.79 \pm 0.38\%$ ). Since these children and adults would typically have no difficulty in distinguishing *b* from *d*, or *p* from *q*, in an untimed test of isolated letter recognition, we expect that these confusions result from the temporal demands of the trigram task or from adjacency of flanking letters (crowding) and have an impact on the size of the visual span.

In a separate preliminary report, based on this data set, we have shown that a decrease in crowding accounts for at least a portion of the growth in the size of visual span profiles across grade levels (Kwon & Legge, 2006). Pelli et al. (in press) have recently presented compelling theoretical and empirical arguments for the important role of crowding in limiting the size of the visual span (they use the term “uncrowded span”), although they did not address developmental changes in the size of the visual span.

In short, relative position errors, orientation errors and crowding may all play a role in developmental changes in the size of the visual span.

#### 4.3. Oculomotor factors

It is also possible that fixation errors could play a role in the observed developmental changes in the size of the visual span. Indeed, it has been reported that children's fixation stability increases with age from 4 to 15 years (Ygge, Aring, Han, Bolzai, & Hellstrom, 2005). If children erroneously fixated leftward or rightward of the intended location in our trigram task, performance would on average, suffer;

the mean distance of trigrams from the fixation point would increase as the size of the fixational error increases. We conducted a simulation analysis to evaluate the impact on the size of the visual span of such fixation errors. The key parameter of the model was the variability in fixation positions, represented by the standard deviation of an assumed Gaussian distribution of fixation locations centered on the correct fixation mark. An average adult visual span was used as an input parameter for each Bernoulli trial to obtain proportion correct for each letter position. Over trials, we computed the size of the visual span in bits of information transmitted. Through 100 repetitions, we obtained the estimates of the size of the visual span for a given fixation error. For example, if the standard deviation was two letter positions ( $\sigma = 2$ ), 68% of the fixation points in the simulated trials would lie within  $\pm 2$  letter positions from the intended fixation mark. As expected the greater the fixation errors (i.e., larger standard deviations), the smaller the size of the resulting visual spans. The simulation results indicated that fixation variability would need to increase from a standard deviation of 0 to more than 3 letter positions to simulate our observed reduction in visual span size from adults to 3rd graders. Moreover, fixation errors of 3 letter spaces for  $1^\circ$  letters would correspond to fixation errors of 12 letter spaces for  $0.25^\circ$  letters, producing devastating effects on the size of the visual span for the smaller print size. Because we did not observe print size effects on the size of the visual span, and because the fixation errors deduced from our simulation seem implausibly large, we doubt that fixation errors account for the developmental differences in the size of the visual span.

We also observed a substantial growth in reading speed across grades even in the RSVP reading where the need for eye movements is minimized. This result also confirms the view that developmental changes in reading speed can not be solely explained by maturation of oculomotor control.

#### 4.4. Non-visual factors

Although we have focused on the size of the visual span as a possible factor influencing reading development, our data indicate that this factor accounts for at most 30–50% of the variance in reading speeds across grade levels. Non-visual cognitive and linguistic factors must also contribute to developmental changes in reading speed. It is possible that accidental correlations of one of these factors with grade level could masquerade as an effect of visual span. For example, if reading speed is correlated with IQ, and some unknown selection bias resulted in increasing mean IQ across grade level, then IQ might underlie the correlations we found between reading speed and visual span. In the case of IQ, this seems highly unlikely. Although we did not control for or measure the IQ of our subjects, we have no reason to suspect that there were increases in IQ across grade levels. Even if such a sampling bias exists, O'Brien et al. (2005) found no effect of IQ on maximum

oral reading speed and critical print size in a group of children (aged 6 to 8) tested with MNREAD sentences similar to those used in the present study.

As another example, it is possible that children's ability to recognize and speak the words used in our testing material varied across grade levels, accounting for the correlation between reading speed and grade level. For example, if children in the lower grades were unable to recognize and articulate words in the test material, even for unlimited viewing time, the missed words would count as errors in our scoring and result in reduced reading speed. We did not test word decoding skills of our subjects on a standardized test such as the subsets of the Woodcock–Johnson III Cognitive and Achievement Batteries (Woodcock, McGrew, & Mather, 2001). We did, however, screen all of our subjects with the MNREAD acuity chart (for a review of its properties, see Mansfield & Legge, 2007). This chart, although designed as a test of the effect of visual factors on maximum reading speed, critical print size and reading acuity, uses simple declarative sentences with vocabulary consisting of the 2000 most frequent words in 1st, 2nd, and 3rd grade text. The sentence material on the MNREAD chart is very similar to the test material in the present study. None of the words was missed or read incorrectly by our children for sentences above their critical print sizes. These observations lead us to conclude that untimed word-decoding skill was not a limiting factor influencing performance across grade levels in our study.

As yet another example of a potential non-visual influence, the oral reporting method used in the trigram task for measuring visual-span profiles might reflect more than the ability to extract visual information. Performance in this task could be influenced by articulation programming, rapid access to letter naming, memory capacity, and reporting accuracy. Many studies using rapid automatized letter naming (RAN) have shown that those component skills are highly correlated with reading performance (e.g., Denckla & Rudel, 1976; Manis, Seidenberg, & Doi, 1999; Wolf, 1991; Wolf, Bally, & Morris, 1986). It is possible that the underlying visual spans are actually stable across school age, but the observed changes in the size of visual-span profiles might be due to some later stages of processing. However, we think this is unlikely. In the trigram task, there was no time pressure to report the letters, so there were no requirements for rapid articulation and no time pressure on access to letter naming codes. It is still possible that younger children might make more phonological errors or transposition errors in reporting due to less efficient memory. Indeed, it is known that overall memory capacity including perceptual-memory improves with increasing age in children (Dempster, 1978; Ross-sheehy, Oakes, & Luck, 2003; Shwantes, 1979). However, convergent evidence has shown that children at the age of 9 are able to hold an average 5 to 6 digits or spatial symbols in their visual memory (e.g., Miles, Morgan, Milne, &

Morris, 1996; Wilson, Scott, & Power, 1987). This result suggests that recalling and reporting a triplet of letters is not likely to pose difficulties for the children in our study. Manis et al. (1999) had 1st and 2nd grade students name 50 digits and letters in a random order aloud as rapidly as possible and measured reporting accuracy. They found that the rate of oral reporting errors was less than 2%, suggesting that by the end of first grade, most children know the names of all the letters and are able to report them with high accuracy.

These considerations encourage us to believe that the observed differences in the size of the visual span across age is likely to represent changes in the availability of bottom-up sensory information rather than effects of later stages of processing. Nevertheless, we cannot rule out the possibility that some other uncontrolled cognitive or other non-visual variable accounted for the apparent association between visual span and reading speed across grade levels in our study.

#### 4.5. Effect of letter size

Finally, we addressed the effect of letter size. We expected that young children would have larger visual spans and read faster with 1° characters than with 0.25° characters. Contrary to our expectation, we found no effect of character size for either reading speed or visual span in children. Apparently, legibility as assessed by these two measures, does not account for the preference of children for larger print in books. It is possible that developmental changes in the effects of print size on reading speed are complete by 3rd grade (age 8–9 years), accounting for the absence of print size effects in our data. Consistent with this possibility, Hughes and Wilkins (2002) found that younger children aged below 7 showed a significant dependence of reading speed on letter size in the range 0.72–1.43° at a viewing distance of 40 cm, but older children above 8 years did not. Similarly, O'Brien et al. (2005) showed that critical print size (CPS) decreased with age from 6 to 8 years old, suggesting younger children need larger print to optimize reading performance. Taken together, it may be the case that the dependence of reading speed on print size becomes adult-like by about 8 years of age.

#### 4.6. Summary

We summarize our conclusions as follows: (1) The visual span grows in size during the school years. (2) Consistent with the visual-span hypothesis this developmental change in the size of the visual span is significantly correlated with the developmental increase in reading speed. (3) Because both RSVP and flashcard reading speed increase with age, the growth in reading speed is unlikely to be due to oculomotor maturation. (4) We found no evidence that the use of larger print in children's books reflects faster reading or larger visual spans for large print.

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#### References

- Adams, M. J. (1990). *Beginning to read: Thinking and learning about print*. Cambridge, MA: The MIT Press.
- Aghababian, V., & Nazir, T. A. (2000). Developing normal reading skills: Aspects of the visual processes underlying word recognition. *Journal of Experimental Child Psychology*, *76*, 123–150.
- Beckmann, P. J. (1998). Preneuronal limitations to identification performance in central and peripheral vision. Ph.D. dissertation (University of Minnesota, Minneapolis, MN).
- Bondarko, V., & Semenov, L. (2005). Visual acuity and the crowding effect in 8- to 17-year-old school children. *Human Physiology*, *31*, 532–538.
- Bouma, H. (1973). Visual interference in the parafoveal recognition of initial and final letters of words. *Vision Research*, *13*, 767–782.
- Brainard, D. H. (1997). The psychophysics toolbox. *Spatial Vision*, *10*, 433–436.
- Cairns, N. U., & Setward, M. S. (1970). Young children's orientation of letters as a function of axis of symmetry and stimulus alignment. *Child Development*, *41*, 993–1002.
- Carver, R. P. (1977). Toward a theory of reading comprehension and rauding. *Reading Research Quarterly*, *13*, 8–63.
- Carver, R. P. (1976). Word length, prose difficulty and reading rate. *Journal of Reading Behavior*, *8*, 193–204.
- Carver, R. P. (1990). *Reading rate: A review of research and theory*. San Diego, CA: Academic Press.
- Cornelissen, P., Bradley, L., Fowler, S., & Stein, J. (1991). What children see affects how they read. *Developmental Medicine and Child Neurology*, *33*, 755–762.
- Davidson, H. P. A. (1934). A study of reversals in young children. *Journal of Genetic Psychology*, *45*, 452–456.
- Davidson, H. P. A. (1935). A study of the confusing letters b, d, p, and q. *Journal of Genetic Psychology*, *47*, 458–468.
- Dempster, F. N. (1978). Memory span and short-term memory capacity: a development study. *Journal of Experimental Child Psychology*, *26*, 419–431.
- Denckla, M., & Rudel, R. G. (1976). Rapid "automatized" naming (RAN): Dyslexia differentiated from other learning disabilities. *Neuropsychologia*, *14*, 471–479.
- Dowdeswell, H. J., Slater, A. M., Broomhall, J., & Tripp, J. (1995). Visual deficits in children born at less than 32 weeks' gestation with and without major ocular pathology and cerebral damage. *British Journal of Ophthalmology*, *79*, 447–452.
- Farkas, M. S., & Smothergill, D. W. (1979). Configuration and position encoding in children. *Child Development*, *50*, 519–523.
- Goswami, U., & Bryant, P. (1990). *Phonological skills and learning to read*. Hillsdale: Erlbaum.
- Hughes, L., & Wilkins, A. (2000). Typography in children's reading schemes may be suboptimal: Evidence from measures of reading rate. *Journal of Research in Reading*, *23*, 314–324.
- Hughes, L. E., & Wilkins, A. J. (2002). Reading at a distance: Implications for the design of text in children's big books. *British Journal of Educational Psychology*, *72*, 213–226.



- Jackson, M. D., & McClelland, J. L. (1979). Processing determinants of reading speed. *Journal of Experimental Psychology: General*, *108*, 151–181.
- Kowler, E., & Martins, A. J. (1985). Eye movements of preschool children. *Vision Research*, *17*, 141–146.
- Kwon, M. Y., & Legge, G. E. (2006). Developmental changes in the size of the visual span for reading: effects of crowding. *Journal of Vision*, *6*, 1003a [Abstract].
- Legge, G. E. (2007). *Psychophysics of reading*. Mahwah, NJ: Erlbaum.
- Legge, G. E., Cheung, S. H., Yu, D., Chung, S. T. L., Lee, H. -W. & Owens, D. P. (2007). The case for the visual span as a sensory bottleneck in reading. *Journal of Vision*, *7*, 1–15. <http://www.journalofvision.org/7/2/9/>.
- Legge, G. E., Hooven, T. A., Klitz, T. S., Mansfield, J. S., & Tjan, B. S. (2002). Mr. Chips 2002: New insights from an ideal-observer model of reading. *Vision Research*, *42*, 2219–2234.
- Legge, G. E., Klitz, T. S., & Tjan, B. S. (1997). Mr. Chips: An ideal-observer model of reading. *Psychological Review*, *104*, 524–553.
- Legge, G. E., Mansfield, J. S., & Chung, S. T. L. (2001). Psychophysics of reading. XX. Linking letter recognition to reading speed in central and peripheral vision. *Vision Research*, *41*, 725–734.
- Legge, G. E., Pelli, D. G., Rubin, G. S., & Schleske, M. M. (1985). Psychophysics of reading. I. Normal vision. *Vision Research*, *25*, 239–252.
- Legge, G. E., Ross, J. A., Luebker, A., & LaMay, J. M. (1989). Psychophysics of reading. VIII. The Minnesota low-vision reading test. *Optometry and Vision Science*, *66*, 843–853.
- Manis, F. R., Seidenberg, M. S., & Doi, L. M. (1999). See Dick RAN: Rapid naming and the longitudinal prediction of reading subskills in first and second graders. *Scientific Studies of Reading*, *3*, 129–157.
- Mansfield, J. S., & Legge, G. E. (2007). The MNREAD acuity chart. In *Psychophysics of reading in normal and low vision* (pp. 167–191). Mahwah, NJ: Lawrence Erlbaum Associate.
- Mansfield, J. S., Legge, G. E., & Bane, M. C. (1996). Psychophysics of reading. XV. Font effects in normal and low vision. *Investigative Ophthalmology & Visual Science*, *37*, 1492–1501.
- Mason, M. (1980). Reading ability and the encoding of item and locations information. *Journal of Experimental Psychology*, *6*, 89–98.
- Mason, M., & Katz, L. (1976). Visual processing of non-linguistic strings: Redundancy effects in reading ability. *Journal of Experimental Psychology: General*, *105*, 338–348.
- McConkie, G. W., & Rayner, K. (1975). The span of the effective stimulus during a fixation in reading. *Perception and Psychophysics*, *17*, 578–586.
- Miles, C., Morgan, M. J., Milne, A. B., & Morris, E. D. M. (1996). Developmental and individual differences in visual memory span. *Current Psychology*, *15*, 53–67.
- Morrison, F. J., Giordani, B., & Nagy, J. (1977). Reading disability: An information-processing analysis. *Science*, *196*, 77–79.
- Muter, V., Hulme, C., Snowling, M., & Taylor, S. (1997). Segmentation, not rhyming, predicts early progress in learning to read. *Journal of Experimental Child Psychology*, *65*, 370–396.
- Neuhaus, G., Foorman, B. R., Francis, D. J., & Carlson, C. D. (2001). Measures of information processing in rapid automatized naming (RAN) and their relation to reading. *Journal of Experimental Child Psychology*, *78*, 359–373.
- O'Brien, B. A., Mansfield, J. S., & Legge, G. E. (2005). The effect of print size on reading speed in dyslexia. *Journal of Research in Reading*, *28*, 332–349.
- O'Regan, J. K. (1990). Eye movements and reading. In E. Kowler (Ed.), *Eye movements and their role in visual and cognitive processes* (pp. 395–453). New York: Elsevier.
- O'Regan, J. K. (1991). Understanding visual search and reading using the concept of stimulus "grain". *IPO Annual Progress Reports*, *26*, 96–108.
- O'Regan, J. K., Levy-Schoen, A., & Jacobs, A. M. (1983). The effect of visibility on eye-movement parameters in reading. *Perception and Psychophysics*, *34*, 457–464.
- Pelli, D. G. (1997). The VideoToolbox software for visual psychophysics: Transforming numbers into movies. *Spatial Vision*, *10*, 437–442.
- Pelli, D. G., Farell, B., & Moore, B. (2003). The remarkable inefficiency of word recognition. *Nature*, *423*, 752–756.
- Pelli, D. G., Tillman, K. A., Freeman, J., Su, M., Berger, T. D. & Majaj, N. J. (in press). Reading is crowded. *Journal of Vision*.
- Rayner, K. (1986). Eye movements and the perceptual span in beginning and skilled readers. *Journal of Experimental Child Psychology*, *41*, 211–236.
- Rayner, K. (1998). Eye movements in reading and information processing: 20 years of research. *Psychological Bulletin*, *124*, 372–422.
- Rayner, K., & Bertera, J. H. (1979). Reading without a fovea. *Science*, *206*, 468–469.
- Ross-sheehy, S., Oakes, L. M., & Luck, S. J. (2003). The development of visual short-term memory capacity in infants. *Child Development*, *74*, 1807–1822.
- Shwantes, F. M. (1979). Cognitive scanning processes in children. *Child Development*, *50*, 1136–1143.
- Skottun, B. C. (2000a). On the conflicting support for the magnocellular-deficit theory of dyslexia. *Trends in Cognitive Sciences*, *4*, 211–212.
- Skottun, B. C. (2000b). The magnocellular deficit theory of dyslexia: The evidence from contrast sensitivity. *Vision Research*, *40*, 111–127.
- Smith, F. (1971). *Understanding reading*. New York: Holt, Rinehart & Winston.
- Spinelli, D., De Luca, M., Judica, A., & Zoccolotti, P. (2002). Length effect in word naming in reading: Role of reading experience and reading deficit in Italian readers. *Developmental Neuropsychology*, *27*, 217–235.
- Stanovich, K. E. (2000). *Progress in understanding reading*. New York: The Guilford Press.
- Stein, J., & Walsh, V. (1997). To see but not to read: The magnocellular theory of dyslexia. *Trends in Neuroscience*, *20*, 147–152.
- Taylor, S. E. (1965). Eye movements in reading: Facts and fallacies. *American Educational Research Journal*, *2*, 187–202.
- Terepocki, M., Kruk, R. S., & Willows, D. M. (2002). The incidence and nature of letter orientation errors in reading disability. *Journal of Learning Disabilities*, *35*, 214–233.
- Tressoldi, P. E., Stella, G., & Faggella, M. (2001). The development of reading speed in Italians with dyslexia: A longitudinal study. *Journal of Learning Disabilities*, *34*, 414–417.
- Wichmann, F. A., & Hill, N. J. (2001a). The psychometric function: I. Fitting, sampling and goodness-of-fit. *Perception and Psychophysics*, *63*, 1293–1313.
- Wilson, J. T. L., Scott, J. H., & Power, K. G. (1987). Developmental differences in the span of visual memory for pattern. *British Journal of Developmental Psychology*, *5*, 249–255.
- Woodcock, R. W., McGrew, K. S., & Mather, N. (2001). *Woodcock-Johnson III*. Itasca, IL: Riverside.
- Wolf, M. (1991). Naming speed and reading: The contribution of the cognitive neurosciences. *Reading Research Quarterly*, *26*, 123–141.
- Wolf, M., Bally, H., & Morris, R. (1986). Automaticity, retrieval processes and reading: A longitudinal study in average and impaired readers. *Child Development*, *57*, 988–1000.
- Ygge, J., Aring, E., Han, Y., Bolzai, R., & Hellstrom, A. (2005). Fixation stability in normal children. *Annals of the New York Academy of Sciences*, *1039*, 480–483.
- Yu, D., Cheung, S. H., Legge, G. E., & Chung, S. T. L. (2007). Effect of letter spacing on visual span and reading speed. *Journal of Vision*, *7*, 1–10. <http://www.journalofvision.org/7/2/2/>.
- Zeno, S., Ivens, S., Millard, R., & Duvvuri, R. (1995). *The educator's word frequency guide*. Brewster, NY: Touchstone Applied Science Associates.