

# The case for the visual span as a sensory bottleneck in reading

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The *visual span for reading* is the number of letters, arranged horizontally as in text, that can be recognized reliably without moving the eyes. The visual-span hypothesis states that the size of the visual span is an important factor that limits reading speed. From this hypothesis, we predict that changes in reading speed as a function of character size or contrast are determined by corresponding changes in the size of the visual span. We tested this prediction in two experiments in which we measured the size of the visual span and reading speed on groups of five subjects as a function of either character size or character contrast. We used a “trigram method” for characterizing the visual span as a profile of letter-recognition accuracy as a function of distance left and right of the midline (G. E. Legge, J. S. Mansfield, & S. T. L. Chung, 2001). The area under this profile was taken as an operational measure of the size of the visual span. Reading speed was measured with the Rapid Serial Visual Presentation (RSVP) method. We found that the size of the visual span and reading speed showed the same qualitative dependence on character size and contrast, reached maximum values at the same critical points, and exhibited high correlations at the level of individual subjects. Additional analysis of data from four studies provides evidence for an invariant relationship between the size of the visual span and RSVP reading speed; an increase in the visual span by one letter is associated with a 39% increase in reading speed. Our results confirm the visual-span hypothesis and provide a theoretical framework for understanding the impact of stimulus attributes, such as contrast and character size, on reading speed. Evidence for the visual span as a determinant of reading speed implies the existence of a bottom-up, sensory limitation on reading, distinct from attentional, motor, or linguistic influences.

Keywords: vision, contrast, character size, visual span, low vision, reading, reading speed

Citation: 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(2):9, 1–15, <http://journalofvision.org/7/2/9/>, doi:10.1167/7.2.9.

## Introduction

This article makes the case for a sensory bottleneck on reading speed. Although it is obvious that visual processing plays a role in reading, it is not so obvious when or how the characteristics of vision limit reading performance. In this article, we argue that a measure of visual letter recognition, termed the *visual span*, imposes a sensory bottleneck on reading speed. The visual span can be defined qualitatively as the number of letters in a line of text that can be recognized reliably without moving the eyes. This article provides evidence for the close relationship between the size of the visual span and reading speed.

## Impact on reading speed of motor, cognitive, and perceptual factors

Reading involves processing of perceptual and linguistic information and requires participation of the motor system. The motor system comes into play through eye movement control and sometimes through manual control (e.g., use of a mouse in scrolling through computer text or use of a handheld magnifier to scan across a line of text). Eye-movement control imposes a ceiling on reading speed because it is known that reading speeds measured with Rapid Serial Visual Presentation (RSVP), in which the need for eye movements is minimized, can be at least three times faster than eye-movement-based reading speed (cf. Rubin & Turano, 1992).

Cognitive and linguistic factors can influence reading speed in at least three ways. First, reading is slower for hard text than easy text (Rayner & Pollatsek, 1989, chapter 4). Undoubtedly, difficult vocabulary and complex ideas cause readers to slow down, especially if they are focusing on comprehension. Even if no such speed–comprehension trade-off is involved, more difficult text (higher grade level) has longer mean word length, which tends to reduce reading speed. Effects of word length on reading speed can be minimized by using a character-based metric for reading speed. Carver (1990) has summarized data that demonstrate that reading speeds are nearly constant across text difficulty when speed is measured in characters per unit time rather than words per unit time, provided that the grade level of the text is below the reader's grade level.

Second, context can make words more predictable and enhance reading speed. For instance, studies have shown that the time to recognize an individual word is influenced by the preceding words in a single sentence (cf. Stanovich, 1980; West & Stanovich, 1978). Other studies have shown that reading speed is 15% to 100% faster for continuous sentences compared with strings of random words (see Sass, Legge, & Lee, 2006, for a brief review).

Third, the reader's strategy affects reading speed. Carver (1990) has shown that instructions, intended to modify the reader's strategy, can have a major impact on reading speed in tests of silent reading of printed passages. Instructions to learn or memorize details will lead to much slower reading than instructions to skim for gist or search for key words.

It goes almost without saying that perceptual factors can influence reading speed. Most people with low vision from eye disease read slowly and laboriously, even with magnified text. Reading problems are the most common presenting symptoms at low-vision clinics (Elliott et al., 1997). People with normal vision have reduced reading speeds if characters are too near their acuity limit, too close to contrast threshold, too crowded together for easy segmentation, or too blurry to resolve.

Letter recognition is a key component of the perceptual front end of reading. There is a large literature on psychophysical and perceptual issues in letter recognition and, now, a growing literature on the psychophysics of reading. Although everyone would agree that letter recognition has something to do with reading, there is very little theory connecting the two. The visual-span hypothesis, discussed in this article and in other reports from our research (Chung, Legge, & Cheung, 2004; Legge, Ahn, Klitz, & Luebker, 1997; Legge, Mansfield, & Chung, 2001; Yu, Cheung, Legge, & Chung, 2007), provides a conceptual bridge between letter recognition and reading speed. We have adopted the theoretical view that letter recognition precedes word recognition in reading and is fundamental to it. We have taken this stance on the grounds of parsimony, recognizing that there is a long debate about the perceptual units in reading (letters,

spelling patterns, words, etc.). Our method for measuring the visual span and our arguments for the value of this concept are rooted in the assumption of the importance of letter recognition to reading. We acknowledge that other attributes of words may play a role in visual processing. For instance, “word shape” is often proposed as being critical, but review of this concept (Legge, 2007, chapter 3, section 9) implies that it is less important than letter recognition. Given the preeminent role of letter recognition in reading, we still acknowledge the influence (direct or indirect) of top–down linguistic or cognitive factors in addition to low-level sensory factors (e.g., the well-known word-superiority effect, Reicher, 1969; Wheeler, 1970).

However, letter recognition by itself may not be sufficient to characterize the perceptual front end of reading. If letter recognition is the only critical perceptual factor, we might expect that as soon as letters cross acuity or contrast threshold, fluent reading should be possible. Research has shown that threshold stimulus values for fluent reading speed are higher than those for simple letter recognition. We often refer to these thresholds as “critical points” for reading and define them by the critical stimulus value required to achieve maximum reading speed. For instance, the critical print size (CPS) in normal central vision is approximately  $0.2^\circ$  (Chung, Mansfield, & Legge, 1998; Legge, Pelli, Rubin, & Schleske, 1985), roughly three times larger than the acuity limit. The critical contrast is between about 5% and 10% Michelson contrast (Legge, Parish, Luebker, & Wurm, 1990; Legge, Rubin, & Luebker, 1987), which is three to six times the threshold contrast for letter recognition. Reading speed declines for stimulus values below the critical points and approaches zero at the threshold for letter recognition.

Why are the thresholds for maximum reading speed higher than the thresholds for letter recognition? What property of reading vision distinguishes simple letter recognition from reading speed? In other words, what attribute of visual processing limits reading speed, above and beyond factors directly influencing letter recognition?

## The visual-span hypothesis

It is known that the spatial layout of letters in text can affect reading, as well as the physical properties of letters themselves. For example, manipulation of spacing between letters affects reading speed (cf. Chung, 2002; Yu et al., 2007). As a second example, arrangement of text letters in vertical columns (“Marquee text”) rather than horizontal rows is known to reduce reading speed by as much as a factor of 2 (Byrne, 2002). These examples indicate why it is likely that both the spatial layout of letters in text and the characteristics of the letters themselves jointly determine the information that can be encoded during one fixation in reading and together limit reading speed.

It has long been known that relatively few letters can be recognized on a line of text during a single fixation, potentially limiting reading speed (Huey, 1908/1968). Huey reported that subjects could recognize words in sentences from 16 to 26 letter positions to the right of fixation and termed this distance the “reading range.” He recognized, however, that both bottom–up sensory factors (particularly the decline in acuity away from fixation) as well as top–down factors (attention, memory, and context) influenced the reading range. Despite an enormous amount of research on reading and letter recognition since 1908, it is still unclear how sensory factors limit reading speed.

McConkie and Rayner (1975) defined the “perceptual span” as the region around fixation in which printed information influences reading behavior. Operationally, the perceptual span refers to the region of visual field that influences eye movements and fixation times in reading. These authors developed an eye-tracking method (the moving-window technique) to estimate that the perceptual span extends 15 characters to the right and 4 characters to the left of fixation (McConkie & Rayner, 1975; Rayner, Well, & Pollatsek, 1980). This large asymmetry of the perceptual span does not imply inferiority of the left visual field; instead, it implies that stimulus factors influencing eye-movement control in reading extend farther to the right of fixation than to the left. This seminal work on perceptual span has spawned a great deal of research on the contributions of oculomotor control and cognitive control in determining reading behavior (cf. Rayner, 1998). For instance, there is a consensus that cognitive factors may account for a substantial portion of the variance in fixation times in reading while oculomotor strategies and visual constraints are important in determining fixation locations in text (Starr & Rayner, 2001). Presumably, sensory factors also contribute to the size of the perceptual span, but because the perceptual span is also sensitive to context effects, and to oculomotor control, it has not usually been employed to study sensory limitations in reading. One exception is the study by Bullimore and Bailey (1995). They studied reading eye movements in patients with macular degeneration. They observed shorter saccades and inferred a reduced perceptual span presumably linked to deficiencies of visual encoding in their subjects.

We propose that a bottom–up sensory limitation on the number of letters that can be recognized without moving the eyes, the visual span, imposes a limitation on reading speed. Think of the visual span as the size of a window in the visual field within which letters can be recognized reliably. The physical characteristics of letters, and their spatial layout, can both affect the size of this window. The visual span provides a theoretical framework for understanding the impact of stimulus attributes, such as character size and contrast, on reading speed. Unlike Huey’s “reading range” or McConkie & Rayner’s “perceptual span,” the visual span characterizes letter

recognition in the absence of oculomotor or contextual factors. To the extent that the size of the visual span is a determinant of reading speed, we argue that it represents a bottom–up sensory limitation on reading, distinct from attentional, motor, or linguistic influences.

We have developed a method, termed the “trigram method,” for operationally measuring the visual span as a profile of letter-recognition accuracy as a function of distance left and right of the midline (Legge et al., 2001, their Experiment 2). This method is designed to be immune to oculomotor and top–down contextual influences and improves upon an earlier and more indirect method for measuring the size of the visual span (Legge, Ahn, et al., 1997). Figure 1 (top) illustrates a trial in the trigram method.

Our stimuli for measuring the visual span are trigrams, random strings of three letters. We use strings of letters rather than isolated letters because they include a key property of text—letters flanked on one side or on both sides by other letters. We measure letter recognition for trigrams at different horizontal locations, with position indicated by the number of letter slots left or right of the midline. For instance, in Figure 1, the trigram “tgu” is positioned with “g” at slot 5. Position 0 corresponds to a letter on the midline. For measurements in peripheral vision, for example, at 10° in the lower visual field, position 0 corresponds to a letter on the midline 10° below fixation.

In a trial, a trigram is presented too briefly (e.g., 100 ms) to permit an eye movement to the trigram target. The

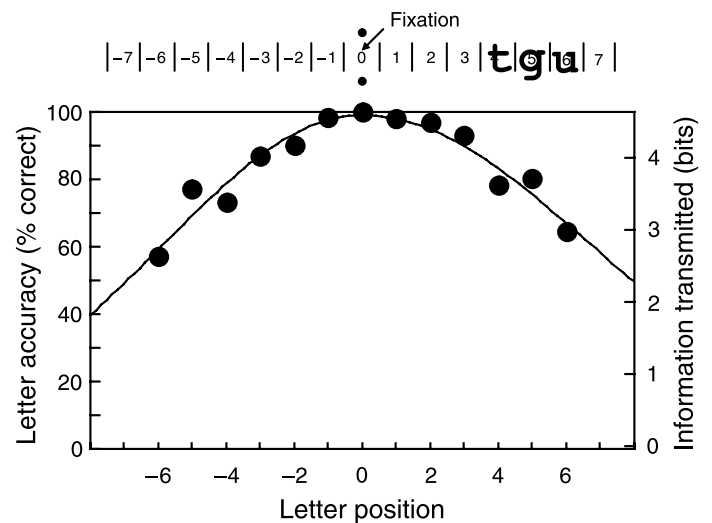


Figure 1. Measuring the visual span with the trigram method. Top: Trials consist of the presentation of trigrams, random strings of three letters, at specified letter positions left and right of fixation. Bottom: A *visual-span profile* is a plot of letter-recognition accuracy (percent correct) as a function of letter position for data accumulated across a block of trigram trials. The right vertical scale shows the transformation from accuracy to information transmitted in bits.

subject is required to report all three letters of the trigram. Across a block of trials, percent correct is accumulated for each letter slot. We refer to the resulting plot of letter accuracy versus letter position as a “visual-span” profile; the smooth curve in Figure 1 is an example. These profiles usually peak at the midline, decline in the left and right visual fields, and are slightly broader on the right of the peak (Legge et al., 2001).

The right vertical scale for the visual-span profile in Figure 1 shows an approximately linear transformation from percent correct letter recognition to information transmitted in bits. The information values range from 0 bits for chance accuracy of 3.8% correct (the probability of correctly guessing 1 of 26 letters) to 4.7 bits for 100% accuracy. For details of this transformation, see Legge et al. (2001). We quantify the size of the visual span by summing across the information transmitted in each slot (similar to computing the area under the visual-span profile in Figure 1). The 13 slots in the sample profile in Figure 1 transmit a total of 50.6 bits. Lower or narrower visual-span profiles will transmit fewer bits of information.

It has been proposed that three sensory mechanisms affect the size of the visual span—decreasing letter acuity in peripheral vision, crowding between adjacent letters, and decreasing accuracy of position signals in peripheral vision. The roles of these factors in determining the size of the visual span are briefly reviewed here and in more detail by Legge (2007, chapter 3). First, it is known that the size of acuity letters grows linearly with retinal eccentricity out to at least 30° (Anstis, 1974; Weymouth, 1958). One consequence is that when letters of any given angular size are placed side by side, as in text, along the horizontal midline, a point will be reached when the more eccentric letters in the string fall below the local acuity limit. This acuity limitation imposes an upper bound on the size of the visual span. For letters of moderate size, typical of text, this upper bound is about 18 letter positions left or right of fixation, implying a full visual span of 36 letters (Legge, 2007). The data presented later in this article and in other cited studies reveal much smaller visual spans. It is clear that factors in addition to declining acuity in peripheral vision contribute to the small size of the visual span.

Second, crowding, sometimes termed “lateral masking,” refers to the interference of flanking letters on the recognition of target letters, an effect that is quite pronounced in peripheral vision (Bouma, 1970; Woodworth, 1938). Bouma estimated that the interfering effects of crowding reduced the functional visual field for letter recognition by a factor of 4. Applying Bouma’s factor to the upper bound on the size of the visual span of 36, imposed by the peripheral decline in acuity, we arrive at an estimate of 9, close to empirical estimates for the size of the visual span under optimal viewing conditions. From these considerations, it seems likely that crowding has a major influence on the size of the visual span. Indeed, in a

preliminary report from our laboratory, we have shown that a reanalysis of data from visual-span profiles provides direct evidence of a major contribution from crowding (Kwon & Legge, 2006). Furthermore, the work of Pelli et al. (2007, submitted for this special issue) also provides a compelling case for the role of crowding in limiting reading.

A third factor that limits the size of the visual span is uncertainty about the relative positions of letters in strings. The strings “cat,” “act,” and “cta” differ only in the spatial order of their letters. Information about letter position must be encoded for proper lexical lookup. Our method for measuring visual-span profiles is sensitive to this positional information because a letter is scored as correct only if it is given in the proper position in the trigram. Errors in the assignment of letter positions within strings have long been known to occur (cf. Estes, 1978) and increase with distance from fixation (Chung, Legge, & Ortiz, 2003).

It is likely that these three factors—peripheral acuity, crowding, and positional uncertainty—interact to determine the size of the visual span. These three factors may respond differently to stimulus variations, such as contrast or light level. While a model of reading speed might be constructed, which refers directly to these variables, we propose that the *visual span* provides a useful summary concept for understanding the influence of sensory factors on reading speed.

Visual-span profiles like the sample in Figure 1 emphasize the restricted spatial extent of the visual field for letter recognition. Temporal factors also influence the visual span. Legge et al. (2001) measured visual-span profiles for different trigram exposure times. In central vision, the profiles increased in amplitude and breadth with increasing exposure time, reaching their maximum spatial extent between about 50 and 100 ms. Visual-span profiles at 10° in the lower visual field required more than 100 ms to reach their maximum size.

A given visual-span profile, based on trials at a given exposure time, describes the information about letter recognition delivered by early sensory processing. The idea is that information about a cluster of nearby letters in text can be processed in a narrow slice of time, probably with some degree of independent analysis for the individual letters. However, purely independent and parallel processing is undoubtedly an oversimplification. For instance, the time course for recognition may be different for letters in different parts of the visual span (Ortiz, 2002; Whitney, 2001; Whitney & Cornelissen, 2005) and certainly at different parts of the visual field (Lee, Legge, & Ortiz, 2003). In addition, crowding represents a form of spatial interaction between letters. These considerations indicate that both time to achieve the maximum spatial profile and the size of the profile may figure as determinants of reading speed.

There are theoretical reasons to expect that the size of the visual span is related to reading speed. Legge, Klitz,



and Tjan (1997) described an ideal-observer model of reading, implemented as a computer simulation named Mr. Chips. This model combines visual, lexical, and oculomotor information optimally to read text in the minimum number of saccades. The size of the visual span is a key parameter of the model. These authors showed that when the model's visual span was reduced in size, there was a corresponding reduction in the model's mean saccade length. Although the Mr. Chips model did not explicitly take time into account, a reduction in mean saccade length would normally be indicative of a reduced reading speed. A succeeding study by Legge et al. (2001) provided further theoretical justification for linking the size of the visual span to reading speed. These authors described a model that used empirically measured visual-span profiles as a front-end description of the visual input and predicted empirical RSVP reading speeds as the output. They applied this model to visual spans and reading speeds measured at several retinal eccentricities. The model demonstrated a clear dependence of reading speed on the size of the visual span. The findings from these two papers provide a theoretical basis for our hypothesis that the size of the visual span is a determinant of reading speed.

Although not a focus of this article, our interest in the concept of the visual span is motivated by the application to low-vision reading. In particular, it is well established that people with central scotomas from macular degeneration usually read slowly (Bullimore & Bailey, 1995; Faye, 1984; Legge, Rubin, Pelli, & Schleske, 1985; Whittaker & Lovie-Kitchin, 1993). People with central scotomas must use peripheral vision for reading. It is likely that reduction in size and distortion of shape of the visual span are major factors accounting for their slow reading.

## Correlation between reading speed and the size of the visual span

The visual-span hypothesis predicts correlated changes in reading speed and the size of the visual span. We will briefly review previous evidence for this correlation. Then, we will describe results from experiments on contrast and character size that also exhibit this correlation.

In this article, and elsewhere, we have often used the RSVP method for measuring reading speed. In RSVP, individual words are presented sequentially at the same location on a display screen. The RSVP rate is controlled by adjusting the exposure time for each word. RSVP reduces or eliminates the role of eye movements in reading, resulting in performance that is more directly influenced by visual factors. It has the added methodological advantage of leaving the rate of stimulus presentation in the hands of the experimenter. RSVP was originally used in cognitive studies of word recognition

in reading (Forster, 1970) and was introduced into psychophysical studies of normal and low vision by Rubin and Turano (1992, 1994). This technique lifts a ceiling on normal reading speed imposed by the latency for eye movements; RSVP reading speeds are typically much higher than speeds for static text. For example, Rubin and Turano (1992) reported an average reading speed of 1,171 words per minute (wpm) for RSVP text compared with 303 wpm for static text. It is known that short passages of RSVP text can be read with the same level of comprehension as text in a standard format (Juola, Ward, & McNamara, 1982; Rubin & Turano, 1992).

Chung et al. (1998) used the RSVP method to measure reading speed in normal peripheral vision (from 0° to 20° in the lower visual field). The question that motivated the study was as follows: Given adequate magnification and a reading task that minimizes oculomotor demand, can peripheral vision match central vision in reading speed? At each eccentricity, reading speed was measured as a function of character size. In all conditions, reading speed increased until a CPS was reached and then leveled out at a maximum value (Chung et al., 1998, their Figure 3). Not surprisingly, the CPS increased in peripheral vision, at a rate roughly comparable to the increase in the size of acuity letters. More important for the present discussion, the maximum reading speeds decreased with increasing retinal eccentricity. Maximum reading speed dropped by about a factor of 6 from central vision to 20° eccentricity, from about 862 wpm in central vision to 143 wpm at 20° in the lower visual field.

What accounts for this decline in reading speed, even when character size exceeds the CPS for the retinal eccentricity in question? According to the visual-span hypothesis, the reduction in reading speed is due, at least in part, to shrinkage of the visual span. An obvious prediction is that the size of visual-span profiles should diminish in peripheral vision. Legge et al. (2001, their Experiment 2) measured visual-span profiles across the same range of eccentricities in the lower visual field of three normally sighted subjects. As predicted, the amplitudes and sizes of the visual spans decreased with increasing retinal eccentricity.

Figure 2 shows how reading speed varies with the size of the visual span, measured in bits of information transmitted in peripheral vision. The reading speeds are mean values from the data of Chung et al. (1998), and the visual-span sizes are mean values from the data of Legge et al. (2001, their Experiment 2). Although the visual-span profiles and reading speeds were obtained from different subjects in different studies, there is a high correlation of .959 between the group means.

A stronger test of the covariation of reading speed and visual-span size would come from a study in which reading speeds vary nonmonotonically with some stimulus dimension and for which both types of measurements are obtained from the same subjects. We conducted such a study in which the independent stimulus dimension was

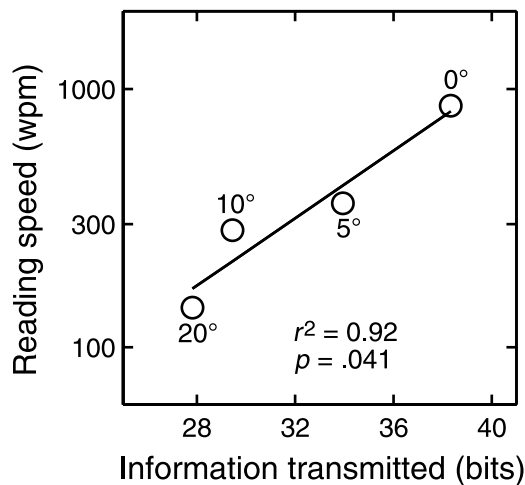


Figure 2. Relationship between reading speed and visual-span size in peripheral vision. A scatter plot is shown for mean RSVP reading speeds ( $\log_{10}$  speeds from the data of Chung et al., 1998) and mean visual-span sizes in bits of information (from the data of Legge et al., 2001) at corresponding retinal eccentricities from 0° to 20° in the lower visual field. Visual spans were measured with 200-ms presentations.

letter spacing (Yu et al., 2007). This study was motivated by a prior study by Chung (2002). Chung tested the idea that extrawide letter spacing in words might reduce crowding and result in faster reading speed, especially in peripheral vision. This prediction was not confirmed; she found that reading speed was slower when interletter spacing was twice the standard value. Increasing the letter spacing should reduce crowding; hence, why does reading slow down? Yu et al. hypothesized that visual-span profiles, measured with extrawide spacing between letters, would be reduced in size and show a dependence on letter spacing similar to reading speed. Yu et al. measured reading speeds (for both RSVP and short blocks of text requiring eye movements termed “flashcards”) using a fixed-width (Courier) font. Testing was conducted for central vision at two print sizes straddling the CPS. Letter spacing ranged from half the standard letter spacing to twice the standard spacing. Both the size of the visual span and reading speed showed a similar nonmonotonic dependence on letter spacing; they increased until standard spacing and then decreased for extrawide spacing. For each of their five individual subjects, there were high correlations between size of the visual span (bits of information) and  $\log$  reading speed, averaging .894 (RSVP) and .925 (flashcard).<sup>1</sup> The results were consistent with the hypothesis that spacing effects on reading speed are due to changes in the size of the visual span.

We note that Yu et al. (2007) found high correlations between size of the visual span and reading speed for both RSVP and blocks of text requiring eye movements. We

have often used RSVP reading because it removes the ceiling on reading speed imposed by oculomotor limitations, presumably exposing sensory limitations. Nevertheless, the Yu et al. findings imply that the size of the visual span is also closely associated with the more conventional eye-movement-mediated reading speed.

We note one more instructive finding from Yu et al. (2007)—a decoupling of letter-recognition performance at fixation and the size of the visual span. Consider the effect of increasing letter spacing from the standard letter spacing to twice the standard spacing ( $2\times$  spacing). In the  $2\times$  spacing condition, letter-recognition performance on the midline (and near the peak of the visual-span profile) was slightly better than that in the standard spacing condition. Nevertheless, the overall size of the visual-span profile (measured in bits of information transmitted) was lower for the  $2\times$  condition. Reading speed was also slower for the  $2\times$  condition. This observation argues for a tighter link between reading speed and the size of the visual span than between reading speed and letter recognition per se.

Finally, in two studies, we have asked whether perceptual learning can be used to enlarge the size of the visual span in peripheral vision and, if so, whether there is a correlated increase in reading speed (Chung et al., 2004; Lee, Gefroh, Legge, & Kwon, 2003). These studies were motivated by the search for a method to increase reading speed in peripheral vision, potentially valuable for people with central-field loss. Chung et al. (2004) tested young, normally sighted adults at 10° above and below fixation. Pre- and posttests consisted of measurements of RSVP reading speed and visual-span profiles at these peripheral-field locations. A training group received four sessions of practice across 4 days, consisting of repeated measurements of visual-span profiles with the trigram task. One training group was trained in the upper visual field, and a second group was trained in the lower visual field. A control group had no training between the pre- and posttests. The trained groups showed an increase in the size of the visual span (average of 6 bits) and a corresponding increase in reading speed (average 40% increase). The control group showed almost no change in visual-span size or reading speed. The transfer of training from the trigram test and associated increase in visual span to reading speed is what would be expected if the visual span imposes a limitation on reading speed. Lee, Gefroh, et al. (2003) performed a replication of this study and included an additional test of the possibility that the training effect was due to improved deployment of spatial attention to peripheral vision. Lee et al. found even stronger training effects than Chung et al., as well as transfer of training from the trigram test to reading speed. Their results did not support the idea that improved deployment of spatial attention to peripheral vision explains the training effects. Together, these two studies add to the convergent evidence that enlargement of the

visual span is associated with an increase in reading speed.

We now present evidence from experiments on text contrast and character size, which adds to this convergent evidence.

## Experiment 1: Contrast effects

As discussed above, there is a gap between contrast thresholds for letter recognition (typically near 1% to 1.5%) and the critical contrast for reading (typically from 5% to 10%). According to the visual-span hypothesis, we expect to find that the size of the visual span increases for contrast levels between the threshold for letter recognition and the critical contrast for reading and then increases no further at higher contrast. In [Experiment 1](#), we measured visual-span profiles and reading speeds for five subjects over a wide range of contrasts from letter-recognition thresholds to 92%.

### Methods

#### Subjects

Five young adults (18 to 32 years of age) with corrected-to-normal vision participated (with letter acuities ranging from 20/13 to 20/17 and Pelli–Robson log contrast sensitivities of either 1.8 or 1.95). They were all native English speakers. All subjects signed an IRB-approved consent form.

#### Stimuli and apparatus

The experiments were controlled by custom software running on a Silicon Graphics O2 workstation or Matlab 5.2.1 using the Psychophysics Toolbox extensions (Brainard, 1997; Pelli, 1997) running on a Power Mac G4 (model: M8570) and displayed on a SONY Trinitron color graphic display (model: GDM-FW900; refresh rate: 76 Hz; resolution: 1,600 × 1,024).

All the letters were rendered in lowercase Courier—a serif font with fixed width. We used a fixed-width font, rather than proportionally spaced font (more typical of modern text), because it has a constant center-to-center spacing between letters, which simplifies the measurement of visual-span profiles.

The characters were displayed as dark stimuli on a white background (50 cd/m<sup>2</sup>), as binary bitmap images. Contrast was controlled by adjusting the gray level of the characters. The correspondence between gray level and luminance (gamma function) was measured with a Minolta CS-100 Chroma Meter. Character contrast is given by the Michelson definition: the difference in luminance between the character and the background divided by their sum.

The character size was 1° (x-height). Viewing was binocular from a distance of 30 cm. Room lights were turned off during testing.

### Three tests

Each subject participated in the following three tests.

1. Contrast thresholds for letters. Thresholds were measured to assess individual differences in contrast sensitivity and to calibrate stimuli in the other tests in multiples of a threshold contrast. The stimuli were trigrams (random strings of three letters), arranged side by side with standard text spacing, with all three having the same contrast. The central letter of the trigram appeared between a pair of vertically separated fixation dots. The trigrams were presented for 100 ms. The subject was required to report the three letters in order from left to right, wherein they have to guess the identity of each letter if they were unsure. Only accuracy on the central letter of the trigram was scored for threshold determination. We used trigrams for measuring letter thresholds, rather than single letters, because we wanted a threshold measurement that was directly comparable to the measurements of visual-span profiles (see below). There were 30 trials at each of six contrasts from 1% to 10%. The data were fit by a psychometric function (cumulative Gaussian), and the contrast yielding 50% correct for the central letter was defined as the contrast threshold  $T$  for letter recognition.
2. Visual-span profiles. Visual-span profiles (see [Figure 1](#) and accompanying text) were measured for five values of character contrast— $T$ ,  $2T$ ,  $4T$ , 30%, and 92%.  $T$  is an individual's contrast threshold for letter recognition (see the previous paragraph). The trigram exposure time was 100 ms. Trigrams were tested with center letters at positions  $-4$  to  $+4$  (9 positions) for contrast  $T$ , at positions  $-5$  to  $+5$  (11 positions) for  $2T$ , and at positions  $-7$  to  $+7$  (15 positions) for the higher three contrast levels. The range of test positions was restricted at the lower contrasts because of the low accuracy on the tails of the profiles. There were 10 blocks of trials, with 2 blocks at each contrast level, ordered from maximum to minimum contrast and from minimum to maximum contrast. In each block, there were 10 trials for each trigram position. This means that a given individual's profile at a given contrast level is based on a number of trials equal to 20 times the number of center positions. Plots of the profiles (such as [Figure 1](#)) show percent correct letter recognition versus position left or right of the midline. Each point accumulates data over trials in which the trigram is centered on the position in question or is centered one position to the left or one position to

the right. (Legge et al., 2001 [their Figure 5], showed results for component visual-span profiles associated with the three letter positions within trigrams.) In the present study, this means that each data point is based on 60 trials. The ordering of trigram trials within a block was randomized, and the selection of the three letters within a trigram was based on a random draw from an equal-probability distribution of the 26 letters of the alphabet.

The visual-span profiles were fit with split Gaussian curves, characterized by three parameters: the amplitude (constrained to lie on the midline) and the standard deviations of the left and right sides.

3. Reading speed. Reading speed was measured for the same character size ( $1^\circ$ ) and set of contrasts used in

the visual-span testing. The RSVP method was used. On each RSVP trial, a single short sentence (average length = 11 words, average word length = 4 letters) was randomly selected from a pool of 2,658 sentences (the same pool used by Chung et al., 1998) and was presented one word at a time (left justified) at the same place on the screen. A mask, “xxxxxxxxxx,” was used before the first word and after the last word to show the location on the screen at which the stimuli would appear. Subjects were instructed to read the sentences aloud as accurately as possible when the stimuli were presented on the computer screen. Participants were allowed to complete their verbalization after the sentence disappeared from the display. Words reported out

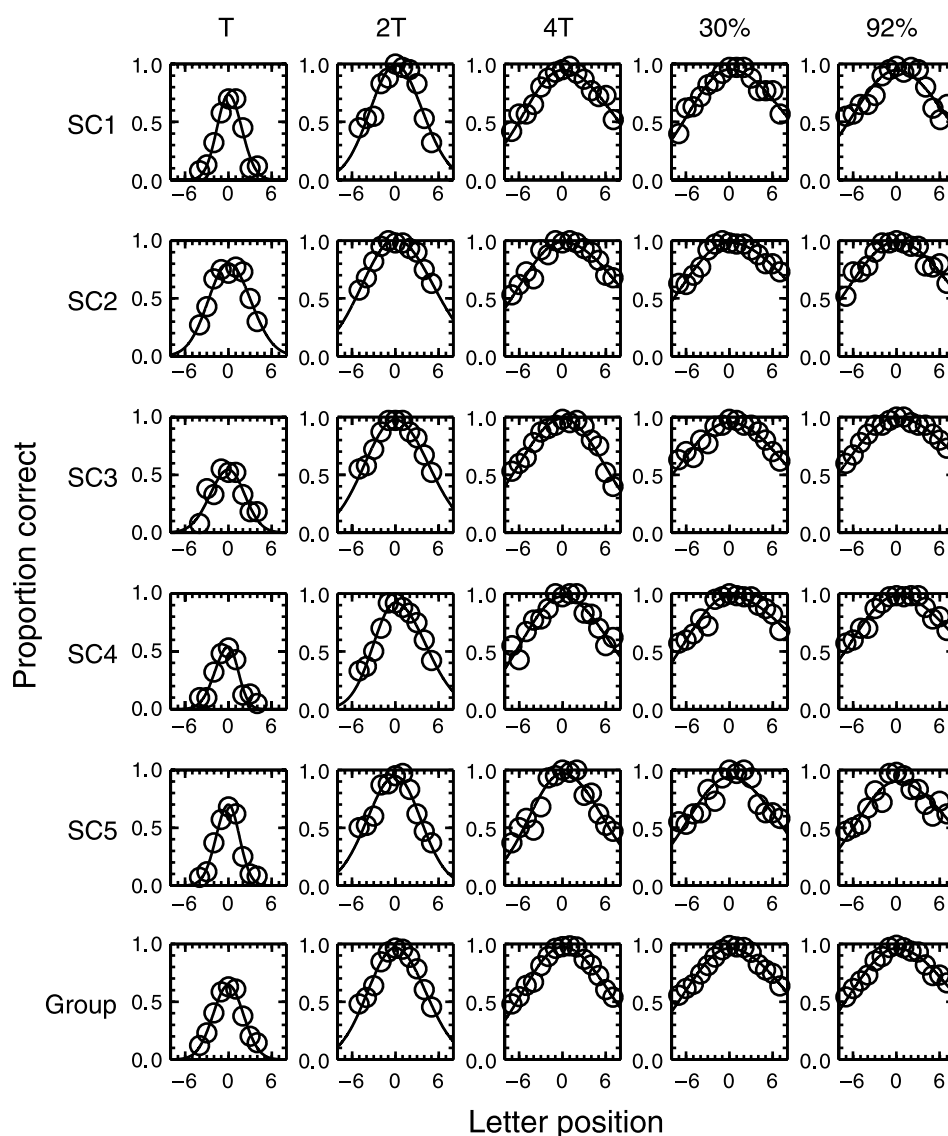


Figure 3. Visual-span profiles are shown for five subjects at five contrast levels. Average values for the group are also shown. Three of the contrast levels are expressed as multiples of the subject’s contrast threshold  $T$  for letter recognition (see the [Methods](#) section). The characters subtended  $1^\circ$ , and the exposure time was 100 ms.



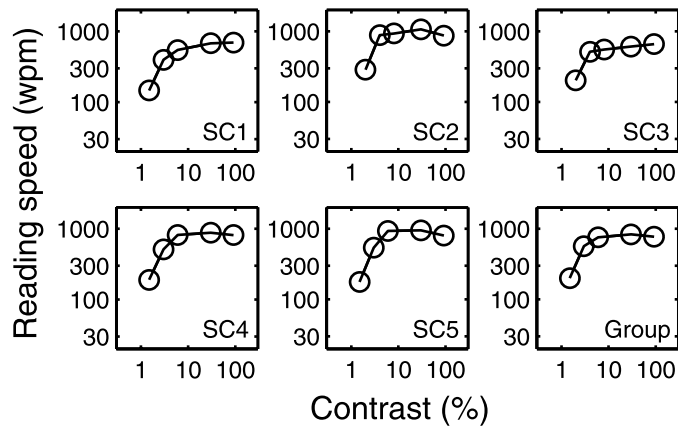


Figure 4. Reading speed (RSVP method) is plotted as a function of text contrast for the five subjects in five panels. Average values for the group are shown in a sixth panel. (The values of the lowest three contrasts varied slightly across the five subjects but are averaged for the group and plotted at 1.5%, 3%, and 6% contrast.) The characters subtended  $1^\circ$ .

of order were counted as correct (e.g., a correction made at the end of the sentence). Subjects were allowed to move their eyes during reading. None of the subjects were tested more than once with any given sentence.

To obtain the reading speed at a given contrast level, we measured the proportion of words read correctly at six RSVP exposure times, which ranged from 40 to 533 ms per word. The specific six exposure times were adjusted within this range, depending on the contrast, so that subjects could read no more than 30% correct at the shortest duration and at least 80% correct at the longest duration. Four sentences were tested at each of the six RSVP exposure times.

We then fit each set of data using a cumulative-Gaussian function from which we derived our criterion reading speed. Each function was based on a total of 24 sentences (4 sentences at each of six durations, with the durations in a random sequence). We derived our criterion reading speed from the RSVP exposure time that yields 80% of words read correctly, as in our previous studies.

## Results

Do reading speed and visual span show the same dependence on stimulus contrast?

Figure 3 shows visual-span profiles for the five contrast levels in Experiment 1—threshold contrast for letter recognition ( $T$ ), two times threshold contrast ( $2T$ ), four times threshold contrast ( $4T$ ), and for high levels of 30% and 92%. The values of  $T$  were 1.5% for Subjects SC1, SC4, and SC5 and 2% for Subjects SC2 and SC3. Five

rows of panels show profiles for the five subjects, and the sixth row shows group data averaged across subjects.

Figure 3 shows that for very low contrasts, the visual-span profiles are narrow. As contrast rises from threshold ( $T$ ) to four times threshold ( $4T$ ), the peak increases to 100% and the profiles broaden; in other words, the visual spans get larger. At even higher contrasts, the profiles remain stable in size and shape.

Figure 4 shows RSVP reading speed results from Experiment 1. Five panels show plots of reading speed versus contrast for the individual subjects, and a sixth panel shows average data for the group. Reading speed rises sharply at very low contrasts and then flattens out above about four times the threshold contrast. This dependence of reading speed on contrast has been shown in previous work (Legge et al., 1990, 1987). For the purposes of the present study, one major finding is that comparison of Figures 3 and 4 indicates that the size of the visual span and reading speed appear to have a very similar dependence on contrast.

In the Introduction, we defined the size of the visual span in terms of the information transmitted in bits (see Figure 1 and related discussion), a measure similar to area under the visual-span profile. Figure 5 shows scatter plots of the size of the visual span (bits of information transmitted) and reading speed for the five contrast levels in Experiment 1. Each panel is for one subject. The correlation between reading speed and visual-span size is high and statistically significant, with the proportion of

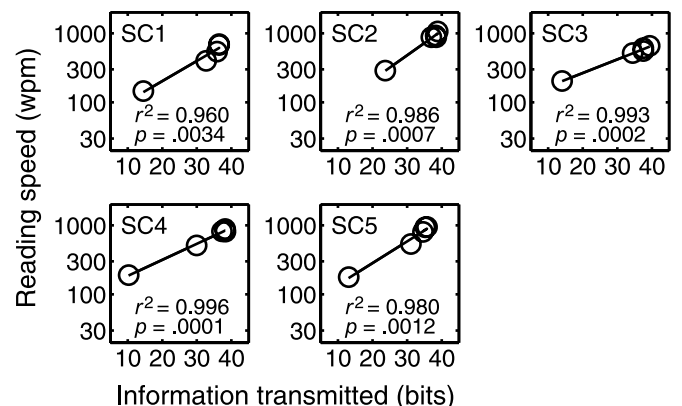


Figure 5. Correlation of reading speed and visual-span size associated with different contrast levels. The five panels show scatter plots of RSVP reading speeds and corresponding visual-span sizes for the five subjects in Figures 3 and 4. Each data point depicts the size of the visual span (bits of information summed across the central nine slots in the visual-span profiles) and corresponding RSVP reading speed ( $\log_{10}$  values) for a given contrast level. The five points in each panel correspond to the five contrast levels in Figures 3 and 4. Regression lines have been fit to the data in each panel. Squared correlation coefficients indicate the proportion of variance accounted for.  $p$  values indicate that all correlations are statistically significant at the .05 level.

variance accounted for ranging from 96% (SC1) to 99.6% (SC4). The high correlations are consistent with the visual-span hypothesis.

## Experiment 2: Character-size effects

There is also a gap between acuity size for letter recognition (often 5 arcmin or less) and the CPS for reading (typically from  $0.2^\circ$  to  $0.3^\circ$ , equivalent to 12 to 18 arcmin). According to the visual-span hypothesis, the size of the visual span should increase for character sizes between the acuity limit for letter recognition and the CPS to achieve maximum reading speed.

It is also known that reading speed slows down when character size exceeds a maximum value, typically about  $2^\circ$  (Legge, Pelli, et al., 1985). The visual-span hypothesis

predicts a corresponding shrinkage in the size of the visual span for very large characters.

In [Experiment 2](#), we measured visual-span profiles and RSVP reading speeds for five subjects over a wide range of character sizes from near the letter-acuity limit to  $4^\circ$ . This experiment provides a more stringent test of the visual-span hypothesis because of the nonmonotonic relationship between reading speed and character size; we predicted a similar nonmonotonic dependence of the size of the visual span on character size.

## Methods

### Subjects

Five undergraduate students (18 to 22 years of age) participated. All were native English speakers. Their letter acuities, measured on the Lighthouse Distance Visual Acuity chart, were as follows: SP1, 20/16; SP2, 20/17; SP3, 20/12.5; SP4, 20/16; and SP5, 20/17. All subjects signed an IRB-approved consent form.

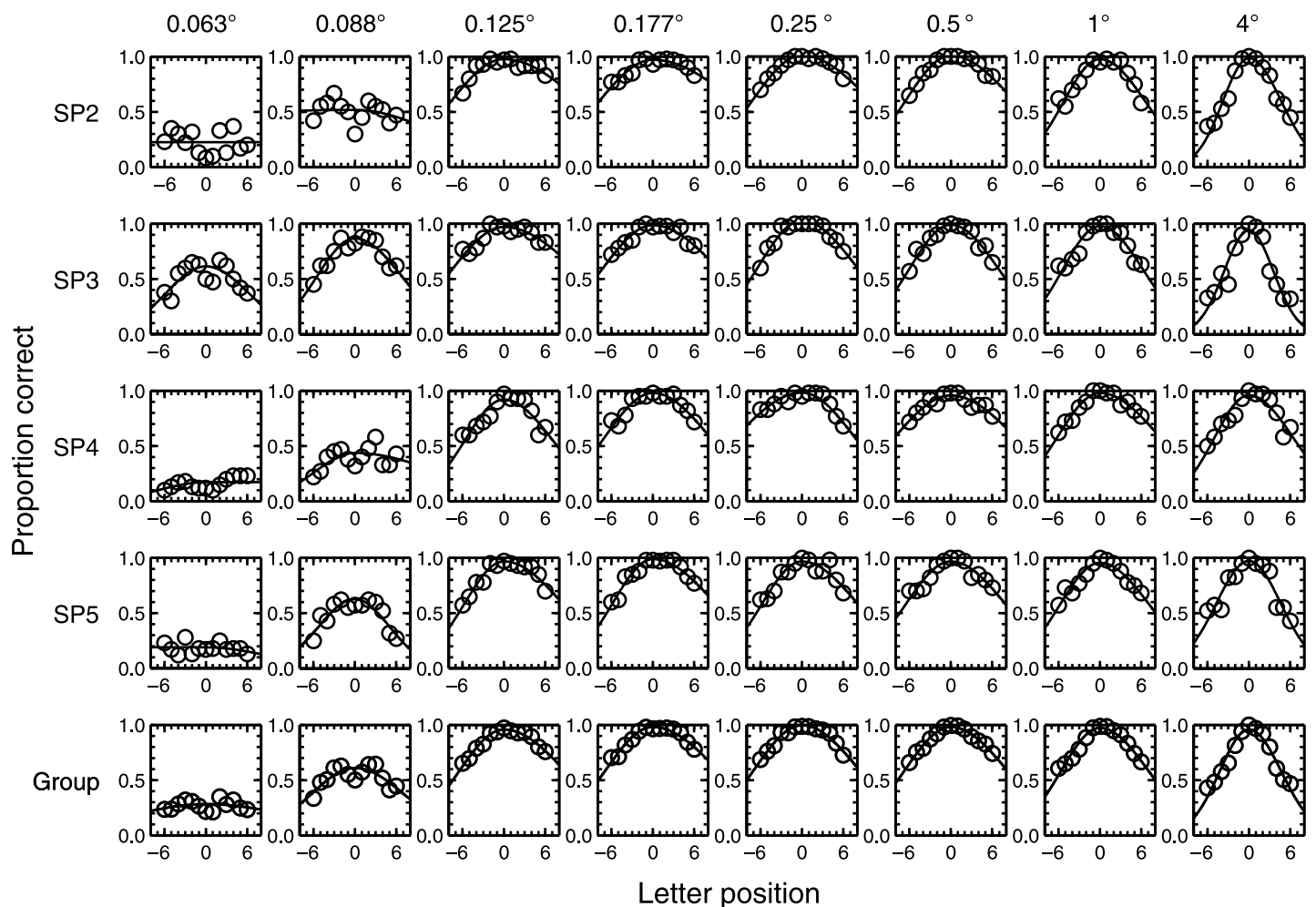


Figure 6. Visual-span profiles are shown for four subjects at eight character sizes. (Data for a fifth subject are not shown because they were obtained for a slightly different set of character sizes; see the [Methods](#) section.) Average values for the group are also shown. The exposure time was 100 ms.

### Stimuli, apparatus, and procedures

The details were like those described above for [Experiment 1](#) with the following important exceptions.

Contrast thresholds for letter recognition were not measured. All stimulus characters were rendered as black characters on a white background ( $60 \text{ cd/m}^2$ ) at a high Michelson contrast of 90%.

For all five subjects, RSVP reading speeds and visual-span profiles were measured at eight character sizes. For Subject SP1, the character sizes were  $0.088^\circ$ ,  $0.125^\circ$ ,  $0.177^\circ$ ,  $0.25^\circ$ ,  $0.5^\circ$ ,  $1^\circ$ ,  $2^\circ$ , and  $4^\circ$ . For the others, the character sizes were  $0.063^\circ$ ,  $0.088^\circ$ ,  $0.125^\circ$ ,  $0.177^\circ$ ,  $0.25^\circ$ ,  $0.5^\circ$ ,  $1^\circ$ , and  $4^\circ$ . Testing at the very small character sizes of  $0.2^\circ$  and less was intended to capture performance between the acuity limit and the CPS. Angular character size was varied through a combination of changing physical size on the display and viewing distances from 17 to 200 cm.

Visual-span profiles were measured with 100-ms trigram exposures, with trigrams centered at positions from  $-7$  to  $+7$  (15 positions), with 20 trials per position. This means that the visual-span profiles were based on 300 trials each.

RSVP reading speeds were measured by the same procedure used in [Experiment 1](#), except that the psychometric functions were based on eight exposure times ranging from 13.3 to 400 ms, with three sentences at each exposure time. The same criterion as in [Experiment 1](#) (exposure time yielding 80% correct words) was used to compute reading speed in words per minute.

## Results

Do reading speed and visual span show the same dependence on character size?

[Figure 6](#) shows visual-span profiles for four subjects and eight character sizes. The bottom row of panels shows group data, averaged across subjects (Subject SP1 is omitted from this figure because he was tested with a slightly different set of character sizes, as described in the [Methods](#) section). The character sizes cover a range of about 60:1, from tiny letters at the acuity limit ( $0.063^\circ$ ,  $\sim 4$  arcmin) to large  $4^\circ$  letters. It is evident that the breadth and amplitude of the profiles increase as character size increases from the tiniest letters (leftmost panels) to about  $0.2^\circ$ . The profiles remain approximately constant in size and shape until the character size of  $1^\circ$ . There is a reduction in the size of the visual span (as measured by bits of information transmitted) between  $1^\circ$  and  $4^\circ$ ,  $t(4) = 5.4423$ ,  $p = .0022$  (one tailed).

[Figure 7](#) shows plots of RSVP reading speed versus character size for the five subjects and average data for the group. Reading speed rises sharply at very small character sizes, flattens out at medium character sizes, and then declines slightly for the largest character size. There is a

reduction in reading speed between  $1^\circ$  and  $4^\circ$ ,  $t(4) = 2.1356$ ,  $p = .049$  (one tailed).

This dependence of reading speed on character size has been shown in previous work<sup>2</sup> (Akutsu, Legge, Ross, & Schuebel, 1991; Legge, Pelli, et al., 1985; Legge, Ross, Luebker, & LaMay, 1989; Legge et al., 1987). For the purposes of the present study, another major finding is that comparison of [Figures 6](#) and [7](#) indicates that the size of the visual span and reading speed appear to have a very similar dependence on character size.

[Figure 8](#) shows scatter plots of the size of the visual span (bits of information transmitted) and reading speed for the different character sizes. Each panel is for one subject. The correlation between reading speed and visual-span size is high and statistically significant for all five subjects, with the proportion of variance accounted for ranging from 80.9% (SP1) to 95.5% (SP5). These high correlations are consistent with the visual-span hypothesis.

## Is there an invariant relationship between reading speed and size of the visual span?

Can we go beyond correlation in tightening the link between reading performance and the properties of the visual span? If the size of the visual span is indeed a causal factor that influences reading speed, then a given change in the size of the visual span, whatever its stimulus origin, should result in the same change in reading speed. We can assess this possibility by examining the slopes of scatter plots of reading speed versus visual-span size, such as those in [Figures 5](#) and [8](#) for different stimulus manipulations. If the slopes of such plots are similar, there is support for an invariant relationship between reading speed and visual-span size.

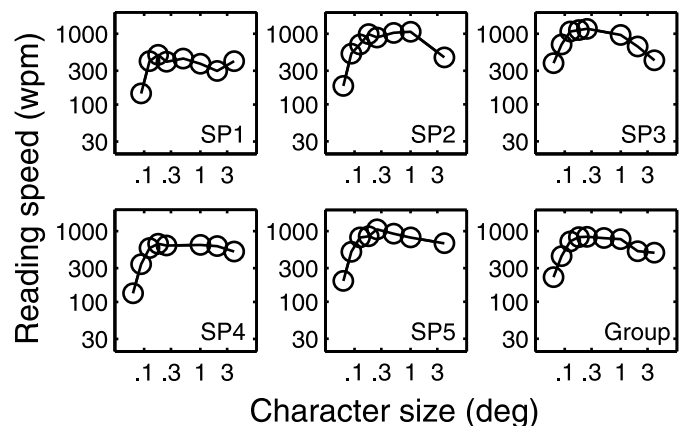


Figure 7. Reading speed (RSVP method) is plotted as a function of character size for the five subjects in five panels. Average values for the group are shown in a sixth panel.

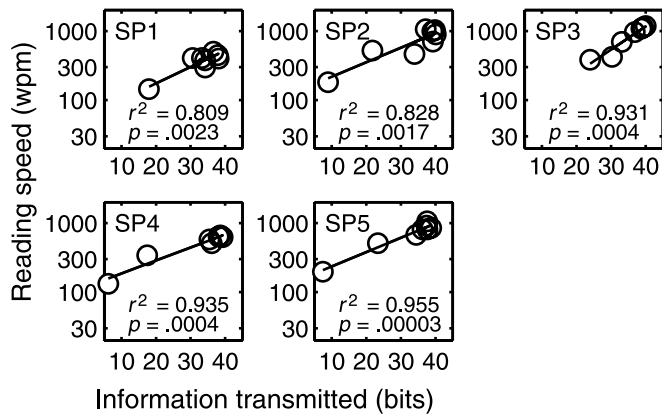


Figure 8. Correlation of reading speed and visual-span size associated with different character sizes. The five panels show scatter plots of RSVP reading speeds and corresponding visual-span sizes for the five subjects studied in Experiment 2. Each data point depicts the size of the visual span (bits of information summed across the central nine slots in the visual-span profiles) and corresponding RSVP reading speed ( $\log_{10}$  values) for a given character size. Regression lines have been fit to the data in each panel. Squared correlation coefficients indicate the proportion of variance accounted for.  $p$  values indicate that all correlations are statistically significant at the .05 level. Note: Because of an experimenter error, there was a mismatch in two of the character sizes for the reading speeds and visual-span profiles for Subjects SP3 and SP4. For these two subjects, the scatter plots contain seven rather than eight points.

Table 1 shows slopes of scatter plots of log RSVP reading speed ( $\log_{10}$  wpm) versus visual-span size (bits of information) for the indicated studies. In all cases, the slopes are means from  $n$  individual subjects. For instance, the first row in Table 1 reports the mean slope from Experiment 1 on contrast in the current article. The slope reported in the table is the mean of the slopes of the scatter plots for the five subjects in Figure 5. In this case,

the mean slope is .028 log wpm per bit. To help interpret this value, recall that 4.7 bits corresponds to one perfectly recognized letter. Thus, a slope of .028 log wpm per bit can be converted to log units of change in reading speed per additional letter in the visual span by multiplying it by 4.7. The mean slope is equivalent to .13 log wpm per letter in this case. In other words, for each additional letter increase in size of the visual span, reading speed increases by about .13 log units, equivalent to a 35% increase in reading speed. This percentage increase in reading speed is shown in the rightmost column of the table.

All the experiments listed in Table 1 were conducted among young adults with normal vision. For all the subjects in all the experiments, RSVP reading speeds and visual-span profiles were measured with the same general methods, except for the factor listed in the first column of the table. (There were other small procedural differences across experiments that probably contributed some additional variability to the results.) Two types of experiments are represented in the table. The contrast, character size, and spacing experiments all involve measurements of reading speed and visual-span profiles in central vision for several values of the independent stimulus variable—contrast, size, and spacing. The spacing experiment by Yu et al. (2007) was discussed in the Visual-span hypothesis section. The perceptual learning study by Chung et al. (2004) refers to measurements of reading speed and visual-span profiles before and after a training regimen (also discussed earlier). For this study, the slopes are based on only two points, that is, the reading speeds and visual-span sizes in the pre- and posttests. Note also that the perceptual learning study was conducted in peripheral vision, either  $10^\circ$  above or  $10^\circ$  below fixation.

An important finding of the table is that all the slopes cluster within a rather tight range, from .024 to .036, with a mean of .030 log wpm per bit. Using the conversion just discussed, the mean slope corresponds to .14 log unit increase in reading speed for each additional perfectly

Changes in visual-span size and RSVP reading speed due to:	Study	$n$	Slope	
			$\log_{10}$ wpm/bit $\pm$ SD	% Increase in reading speed/letter
Character contrast	Experiment 1 (this study)	5	.028 $\pm$ .006	35.4
Character size	Experiment 2 (this study)	5	.024 $\pm$ .006	29.7
Character spacing	Yu et al. (2007)	5	.034 $\pm$ .010	44.5
Perceptual learning, lower visual field	Chung et al. (2004) <sup>a</sup>	6	.029 $\pm$ .010	36.9
Perceptual learning, upper visual field	Chung et al. (2004)	6	.036 $\pm$ .010	47.7
Overall		27	.030	38.8

Table 1. Slopes of log reading speed versus visual-span size. Note: <sup>a</sup>Chung et al. (2004) used a design in which separate groups of subjects received perceptual training in the upper and lower visual fields; there was also a control group with no training. All groups received pre- and posttests in both the upper and lower visual fields. The slopes in the table refer to pre-/post change only in the trained visual field (e.g., upper visual field for subjects trained in the upper visual field).



recognized letter in the visual span, equivalent to a 39% increase in reading speed.

The similarity in slopes across experiments implies a nearly invariant relationship between changes in the visual span and changes in reading speed, regardless of the underlying stimulus factor. This finding strengthens the case for treating the size of the visual span as a causal factor influencing reading speed.

## Concluding remarks

The visual span is a theoretical construct for describing the visual information for letter recognition in reading. It can be thought of qualitatively as a small sampling window within which reliable letter recognition is possible. Reading involves moving this sampling window through text, relying on either eye movements or some type of automated text presentation such as RSVP.

A priori, we cannot be sure what, if any, relationship the visual span has to reading. We might expect that the smaller the “sampling window,” the more samples would be required to process the text, and the slower would be the reading speed. This intuition led us to hypothesize that the size of the visual span is an important factor that limits reading speed.

To investigate this hypothesis, we developed a letter-recognition procedure (trigram method) to create visual-span profiles. We use an information-theory metric to represent the size of the visual span, equivalent to computing the area under the visual-span profiles. This method for measuring the size of the visual span is immune to oculomotor and contextual influences. We have investigated the relationship between the size of the visual span and reading speed.

Our strategy in several studies has been to parametrically vary some stimulus variable and then determine if the size of the visual span and reading speed show correlated changes. Earlier in this article, we reviewed studies of the effects of retinal eccentricity (Chung et al., 1998; Legge et al., 2001), letter spacing (Yu et al., 2007), and training of peripheral vision (Chung et al., 2004; Lee, Gefroh, et al., 2003). In all of these studies, there were highly correlated changes in reading speed and the size of the visual span. Experiments 1 and 2 of this article extended the approach to the effects of character contrast and character size. Here, again, reading speed and size of the visual span showed highly correlated changes in response to the stimulus variable. The studies of spacing effects (Yu et al., 2007) and character size (Experiment 2 of this article) are particularly revealing because both reading speed and the size of the visual span show the same nonmonotonic dependence on the stimulus variables.

The evidence from these studies for a link between the visual span and reading speed is correlational and does not necessarily mean that the size of the visual span

determines reading speed. The convergence of results from several studies, all consistent with a causal link, does build our confidence in the visual-span hypothesis. Additional evidence for a causal link comes from our finding (Table 1) that there is a nearly invariant relationship between changes in the size of the visual span and changes in reading speed. The data from several studies, summarized in Table 1, indicate that an increase in the size of the visual span by one highly recognizable letter is associated with an increase in reading speed by about 40%. This relationship appears to be invariant for changes in visual span mediated by several different stimulus dimensions and would be unlikely to occur for incidental correlations between reading speed and visual-span size. We conclude that the totality of evidence presented in this article provides strong support for the visual-span hypothesis.

Finally, we comment that the correlated dependence of visual-span size and reading speed on important stimulus dimensions (contrast, character size, and retinal eccentricity) strongly implies that both are constrained by early sensory coding in the visual pathway. The influence of contrast coding, spatial-frequency processing, and retinal inhomogeneity on the properties of the visual span and reading speed is reviewed in detail by Legge (2007, chapter 3). The results of the present article imply that early sensory factors do impose a bottleneck on reading speed through the mediating influence of the visual span.

## Acknowledgments

This research was supported by NIH Grants EY02934 (to G.E.L.) and EY12810 (to S.T.L.C.). A preliminary report of the results was given at the 2002 annual meeting of the Vision Sciences Society (Legge, Lee, Owens, Cheung, & Chung, 2002). A portion of the results from Experiment 2 comprised Dan Owens’s honors undergraduate thesis in the College of Biological Sciences at the University of Minnesota.

Commercial relationships: none.

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## Footnote

<sup>1</sup>These correlations were based on visual-span sizes computed from the central nine slots for consistency with other calculations in this article.

<sup>2</sup>The previous studies used either a drifting-text method or a static “flashcard” method. The present results generalize the findings to RSVP.

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