Effect of letter spacing on visual span and reading speed

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S. T. L. Chung (2002) has shown that rapid serial visual presentation (RSVP) reading speed varies with letter spacing, peaking near the standard letter spacing for text and decreasing for both smaller and larger spacings. In this study, we tested the hypothesis that the dependence of reading speed on letter spacing is mediated by the size of the visual span—the number of letters recognized with high accuracy without moving the eyes. If so, the size of the visual span and reading speed should show a similar dependence on letter spacing. We tested this prediction for RSVP reading and asked whether it generalizes to the reading of blocks of text requiring eye movements. We measured visual-span profiles and reading speeds as a function of letter spacing. Visual-span profiles, measured with trigrams (strings of three random letters), are plots of letter-recognition accuracy as a function of letter position left or right of fixation. Size of the visual span was quantified by a measure of the area under the visual-span profile. Reading performance was measured using two presentation methods: RSVP and flashcard (a short block of text on four lines). We found that the size of the visual span and the reading speeds measured by the two presentation methods showed a qualitatively similar dependence on letter spacing and that they were highly correlated. These results are consistent with the view that the size of the visual span is a primary visual factor that limits reading speed.

Keywords: visual span, reading speed, letter spacing, visual crowding

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Introduction

Spacing of letters in text influences reading speed in normal central and peripheral vision (Arditi, Knoblauch, & Grunwald, 1990; Chung, 2002; Legge, Rubin, Pelli, & Schleske, 1985) and in low vision (Legge et al., 1985). Increasing letter spacing beyond separations normally found in text slows reading speed (Chung, 2002; Legge et al., 1985). This is surprising because increased letter spacing reduces crowding, the interference with letter recognition from adjacent letters, and improves letter-identification performance (Bouma, 1970; Chung, Levi, & Legge, 2001). In this study, we show that the size of the visual span (the number of letters in text that can be recognized without moving the eyes) can account for the observed effects of letter spacing on reading speed.

Chung (2002) measured rapid serial visual presentation (RSVP) reading speed for five letter spacings at the fovea and 5° and 10° eccentricities in the lower visual field. Her results showed that reading speed in both central and peripheral vision did not increase with letter spacing beyond the standard spacing (the spacing used in normal Courier text: 1.16 times the width of the lowercase x). In fact, reading speed in central vision declined at larger spacings. Legge et al. (1985) obtained similar results by using the drifting-text method. They measured reading speed with three different letter spacings (1×, 1.5×, and 2× standard) for two normal and four low-vision participants. For all participants, reading speed was highest for the standard spacing and decreased for larger spacings.

The visual span for reading refers to the number of adjacent letters that can be recognized reliably without moving the eyes. Legge, Ahn, Klitz, and Luebker (1997) hypothesized that shrinkage in the size of the visual span could account for slower reading for low-contrast text. They measured reading time as a function of the length of the words used in RSVP reading at different luminance contrast levels. From these reading time versus word length functions, Legge, Ahn, et al. (1997) estimated that the visual-span size decreased from 10 characters to 2 characters as contrast decreased from 100% to 5%. Legge, Mansfield, and Chung (2001) introduced a more direct method for measuring the visual span, based on plots of letter-recognition accuracy as a function of distance left and right of the midline. These plots were termed visual-span profiles. (This method is described in the Methods section.) These authors showed that visual-span profiles shrink in size in peripheral vision, potentially accounting for the corresponding decline of reading speed in peripheral vision (Chung, Mansfield, & Legge, 1998). Legge et al. (2001) also formulated a computational model that links the

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size of the visual-span profiles to RSVP reading speed and proposed that the size of the visual span imposes a bottleneck on reading speed.

The concept of visual span expresses the intuitively plausible idea that reading speed is influenced by the number of letters that can be recognized on one glance; it is a kind of "window size" limitation or sampling limitation on reading. This general idea has been widely accepted as a qualitative limitation on reading from the work of Javal in the 19th century, who recognized that saccadic eye movements functioned to move this sampling window along a line of text (for a review, see Huey, 1908/1968). Until recently, nobody has quantified this limitation on reading. Three sensory mechanisms almost certainly affect the size of the visual span—decreasing letter acuity outward from the midline, 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 have been reviewed by Legge (2007). Increased letter spacing reduces crowding, but it also extends the text further into peripheral vision, which has reduced acuity and reduced positional accuracy. A priori, it is not clear how an increase in letter spacing would affect the size of the visual span for reading. According to the hypothesis that visual span is the primary sensory limitation on reading speed, we predicted that reading speed should show the same dependence on letter spacing as visual-span size. The primary goal of this study was to test this prediction in central vision by measuring both the size of the visual span and reading speed as a function of letter spacing.

Arditi et al. (1990) have argued that crowding occurs in central vision near the acuity limit. If spacing effects are due to crowding, we would expect more pronounced spacing effects for print sizes near the acuity limit. To test this idea, Chung (2002) used two print sizes in her study: one larger and one smaller than the critical print size (CPS). The CPS is the point above which print size is not a limiting factor for reading speed. Chung found an interaction effect between letter spacing and print size for RSVP reading such that a letter spacing that is smaller than the standard adversely affects smaller print size more than the larger print size. In this study, we also used two print sizes (one above and one below the CPS) to test the interaction effect of letter spacing and print size on reading speed and visual-span size. Because crowding is more prominent at the smaller print size, we expected that small letter spacings would limit the visual span and reading speed more for the smaller print size than for the larger print size.

The primary evidence that links visual span and reading speed has been obtained with the RSVP method in which eye movements are minimized (Chung et al., 1998; Legge et al., 2001; Legge, Cheung, Yu, Chung, Lee, & Owens, in press). RSVP presents words one at a time in the same position in the visual field. However, most everyday reading requires saccadic eye movements. It is possible that a linkage between reading speed and visual-span size for RSVP reading would not generalize to reading with saccades. Characteristics of eye-movement control may influence the relationship between visual span and reading speed for everyday reading. Legge, Klitz, and Tjan (1997) and Legge, Hooven, Klitz, Mansfield, and Tjan (2002) have formulated a computational model ("Mr. Chips") to simulate saccade planning with different visual-span sizes. In general, larger visual spans predict larger saccades. On the basis of this model, we would also expect to find a close linkage between the size of the visual span and saccade-based reading speed. A secondary goal of this study was to evaluate this expectation.

To summarize, we tested three predictions: (1) visual-span size and reading speeds have the same dependence on letter spacing; (2) this association generalizes from RSVP reading to reading with eye movements; and (3) letter spacing has different limitations on reading speeds and visual spans for print sizes above and below the CPS.

Methods

Participants

There were five participants with normal or corrected-to-normal vision. Table 1 shows age, gender, binocular values of distance visual acuity (measured using the Lighthouse distance visual acuity chart), log contrast sensitivity (Pelli–Robson contrast sensitivity chart), and three measures from the MNREAD Reading Acuity chart. All participants were native English speakers. The experimental purpose and procedures were explained to the participants before written consent was obtained from each participant. Participants S1, S4, and S5 had prior experience in reading with the

Participant	Age (years)	Gender	Visual acuity (logMAR)	Log contrast sensitivity	MNREAD reading acuity (logMAR)	MNREAD maximum reading speed (wpm)	MNREAD CPS (logMAR)
S1	19	M	−0.18	1.95	−0.18	181	0.0
S2	24	F	−0.12	1.95	−0.10	234	0.1
S3	23	F	−0.14	1.95	0.00	189	0.1
S4	34	F	−0.24	2.10	−0.24	193	−0.1
S5	28	M	−0.22	2.10	−0.23	239	0.0

Table 1. Characteristics of participants.

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RSVP paradigm, and participants S1 and S4 had prior experience with the trigram test, but none had prior experience with the nonstandard letter spacing stimuli used in this study.

Apparatus and stimuli

We generated the stimuli and controlled our experiments using Matlab (version 5.2.1) with the Psychophysics Toolbox extensions (Brainard, 1997; Pelli, 1997). The stimuli were presented using a Power Mac G4 (model: M8570) and a SONY Trinitron color graphic display (model: GDM-FW900; refresh rate: 76 Hz; resolution: 1,600 × 1,024).

All the stimuli were rendered in lowercase Courier—a serif font with fixed width—and displayed at a Michelson contrast of about 99.75% as black characters on a white background (89 cd/m^2). We used a fixed-width font, rather than a proportionally spaced font (more typical of modern text), because it has a constant center-to-center spacing between letters. We were then able to manipulate spacing by varying these center-to-center values. The four letter spacings used in our study were 0.5×, 0.707×, 1×, and 2× standard letter spacing.

We tested two different print sizes in the experiment. The small print size (lowercase x-height equals 0.08°) had a physical size of 0.28 cm, and the large print size (x-height equals 0.15°) had a physical size of 0.52 cm. The viewing distance was 200 cm. The x-heights in pixels were 10 and 18, respectively.

A) Trigram

0.5× fos   0.707× fos

1× fos   2× f o s

B) RSVP

0.5× fossils   0.707× fossils

1× fossils   2× f o s s i l s

C) Flashcard

0.5×
fossils are a
kind of diary
from the past
million years

0.707×
fossils are a
kind of diary
from the past
million years

1×
fossils are a
kind of diary
from the past
million years

2×
f o s s i l s   a r e   a
k i n d   o f   d i a r y
f r o m   t h e   p a s t
m i l l i o n   y e a r s

(Letter spacings are multiples of "standard")

Figure 1. Examples of (A) trigram, (B) RSVP, and (C) flashcard stimuli at four different letter spacings (multiples of standard letter spacing).

RSVP reading speed

In 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 (2002) and Chung et al. (1998), and presented one word at a time (left justified) at the same vertical position on the screen. A mask, "xxxxxxxxxxxxxxx," was presented before the first word to indicate the location on the screen at which the stimuli would appear and after the last word of each sentence.

Flashcard reading speed

The flashcard paradigm was used to measure reading speed using the computerized MNREAD procedure (Legge, Ross, Luebker, & LaMay, 1989). As shown in Figure 1C, each 56-character sentence is rendered on four lines and each line has 14 characters including spaces and an implied space at the end of each line. There were 411 different sentences available for presentation, with an average length of 11.5 words per sentence and an average word length of 4 letters. Before the beginning of each trial, an underscore was used to indicate where the first letter of the sentence would appear.

In both RSVP and flashcard tests, none of the participants read any sentence more than once.

To obtain the reading speed corresponding to a certain text condition (combination of presentation method, print size, and letter spacing), we measured the proportion of words read correctly at different exposure times, which increased in constant log steps, using the method of constant stimuli. The range of exposure times was chosen so that the participants could read no more than 30% correct at the shortest duration and at least 80% correct at the longest duration. The resulting data were fit with a psychometric function to obtain the reading speed. More details are given in the Procedures and data analysis section.

Visual-span measurement

Visual-span profiles were measured with a letter-recognition task using trigrams. Trigrams are strings of three letters, selected at random from among the 26 lowercase letters of the English alphabet. We used trigrams instead of single letters because they are more representative of the format of letters in reading, where most letters are flanked by other letters on one side or on both sides. As Figure 2 shows, letter positions along a horizontal line were marked by the number of letter slots left (negative values) or right (positive values) from fixation. The position of each trigram was indexed by the middle letter. For example, in Figure 2, the position of trigram "chb" is 0 because letter "h" is in letter position 0. Letters "c" and "b" are in letter positions −1 and 1, respectively. The trigram was presented for an exposure time of 100 ms. Before each

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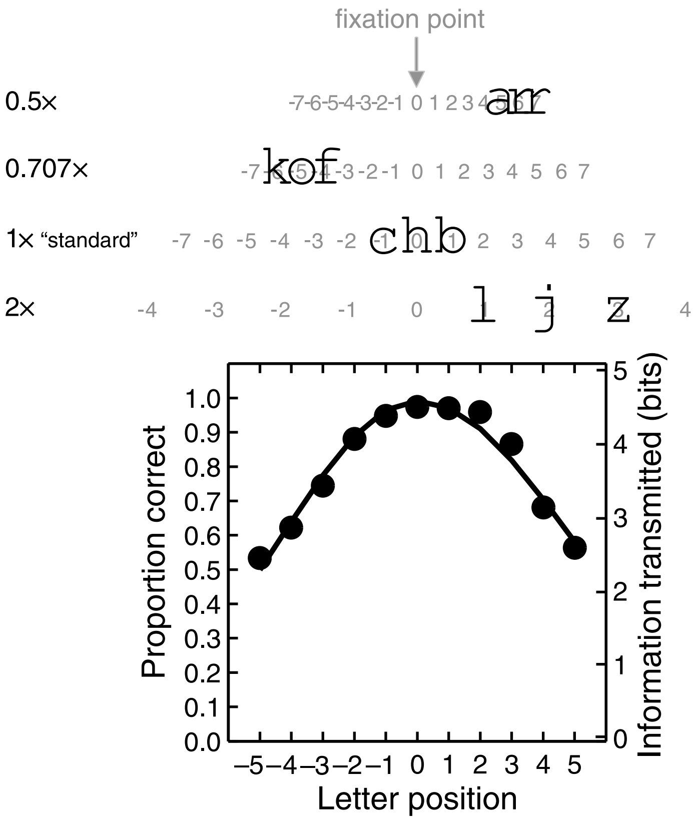

Figure 2. Examples of trigrams presented at different positions (upper) and a sample visual-span profile (lower). Trigram position is specified as the number of letter positions left or right of the midline. For example, the position of the trigram "ljz" is at position 2, which means that the positions of the three letters are 1, 2 and 3, respectively. A visual-span profile is constructed from a series of trigram trials by compiling proportion correct letter recognition (left vertical scale) as a function of letter position. The right vertical scale shows a transformation to information transmitted in bits (see text for details).

trial, three underscores showed the position of the next trigram. The middle letter of the trigram could be located at any letter position from −6 to 6. Figure 2 shows trigrams at four different letter spacings.

Procedures and data analysis

All computer-based tests were done with binocular viewing in a dark room. Each participant took part in four sessions. For the reading tests, participants 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. If words in the sentence were reported out of order, for example, a correction made at the end of the sentence, credit was given for being correct. Participants were allowed to make eye movements during reading.

The first session was devoted to measuring the CPS, which is defined as the smallest print size that yields the maximum reading speed. The CPS was measured for each participant because we wanted to confirm that the two print sizes (0.08° and 0.15°) used in the main experiment straddled the participants' CPS values. We measured RSVP and flashcard reading speeds as a function of print size at the standard letter spacing. Six print sizes, in steps of $\sqrt{2}$, were used: 0.063°, 0.088°, 0.125°, 0.177°, 0.25°, and 0.35°, which covered the range of CPS measured by Chung (2002) and Chung et al. (1998). There were five exposure times per print size and four sentences (participant S1 did three sentences) per exposure time. Each participant was given a few minutes to practice before starting the test. Data from the practice trials are not included in this paper.

In sessions 2, 3, and 4, eight stimulus conditions (two print sizes × four letter spacings) were tested. For each of the eight stimulus conditions, performance was measured on three tasks—RSVP reading speed (measured for six exposure times and six sentences per exposure time), flashcard reading speed (measured for six exposure times and five sentences per exposure time), and trigram measurements to compile a visual-span profile (one profile was based on 234 trials, 13 positions, and 18 trials per position). There were 136 blocks of trials (48 blocks for the RSVP test, 40 blocks for the flashcard test, and 48 blocks for the trigram test). Fewer trials and blocks for flashcard reading were tested because we had fewer sentences in the flashcard sentence pool. The 136 blocks were divided into three sessions, and each session included 16 blocks of flashcard (8 blocks of flashcard in the first session), RSVP, and trigram trials. Every session was divided into halves. In the first half, the conditions with the larger print size were tested first, followed by the conditions with the smaller print size. For each print size, letter spacing was tested in a descending order, starting with the largest letter spacing. The order was reversed in the second half. The trial order in the first session was trigram (T), flashcard (F), RSVP (R), RSVP, and trigram. In sessions 2 and 3, the orders were FRTTRF and RTFFTR, respectively. All five participants were tested using the same sequence.

For both RSVP and flashcard reading, we computed reading speed from the exposure time that yielded 80% of the words read correctly on the fitted psychometric function. Reading speed was computed according to the following equation:

$$\text{Reading speed (in words per minute)} = \frac{60}{\text{Criterion exposure time for word (in seconds)}}.$$

For flashcard reading, criterion exposure time for word equals criterion exposure time for sentence (in seconds) divided by 11.5, which is the average number of words per sentence across all the 411 flashcard sentences in the pool.

The trigram method was used to measure visual-span profiles of participants. A sample is shown in Figure 2. During

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Participant	RSVP CPS (°)	Flashcard CPS (°)	Maximum reading speed (wpm) RSVP	Maximum reading speed (wpm) Flashcard	Ratio of RSVP to flashcard reading speed
S1	0.10	0.10	799	629	1.27
S2	0.10	0.11	730	505	1.45
S3	0.09	0.09	704	501	1.41
S4	0.11	0.10	1101	957	1.15
S5	0.08	0.09	625	438	1.43
M ± *SD*	0.10 ± 0.01	0.10 ± 0.01	792 ± 184	606 ± 208	1.34 ± 0.13

Table 2. CPS and maximum reading speed for each participant and presentation method.

a trigram trial, participants were instructed to fixate between two vertically separated fixation dots. The participant was required to report all three letters from left to right following the presentation of a trigram. A letter was counted as correct only when it was reported in the correct position.

Visual-span profiles are plots of proportion correct letter recognition from the trigram trials as a function of horizontal position left and right of the midline. Only data from the central 11 letter positions (from position −5 to 5) were used in plotting. At each of these letter positions, there were 18 trials in which the letter presented belonged to the outer, middle, or inner letter of the trigram. Thus, each data point was based on 54 trials. As shown in Figure 2, split Gaussians were used to fit the plot with three parameters: the amplitude, left-side standard deviation, and right-side standard deviation. The resulting curve is called a visual-span profile (Legge et al., 2001).

We quantified the size of the visual span by calculating the bits of information transmitted by it (Figure 2). Information transmitted at a given slot on the visual-span profile ranged from 0 bits (for chance accuracy of 3.8% correct) to 4.7 bits (for 100% accuracy). Proportion correct letter recognition was transformed to bits of information using letter-confusion matrices measured by Beckmann (1998), who computed the mutual information associated with confusion matrices. A plot of mutual information versus proportion correct letter recognition was well fitted by a straight line (mutual information = −0.036996 + 4.6761 × proportion correct letter recognition) and was used to transform proportion correct letter recognition to bits of information. We quantify the size of the visual span by summing across the information transmitted by the 11 slots of the profile (similar to computing the area under the profile).

Results

Determining the CPS

Table 2 lists the values of CPS and the corresponding maximum reading speeds.

The CPS measured by the RSVP and flashcard methods showed no significant difference, $t(4) = -0.85$, two tailed, $p = .44$. Across the five participants and two presentation methods, the CPS ranged from 0.08° to 0.11° and the mean CPS was 0.10° ± 0.01° (*SD*). These data are similar to those measured by Chung (2002). From the results, a print size of 0.15° exceeded the CPS value and a print size of 0.08° was smaller than or equal to the CPS value for all participants, justifying our use of 0.08° and 0.15° as the representatives for print sizes smaller and larger than the CPS.

Reading speed versus letter spacing

Reading speed is plotted as a function of letter spacing for RSVP and flashcard presentation methods in Figure 3 (small print size, 0.08°) and Figure 4 (large print size, 0.15°).

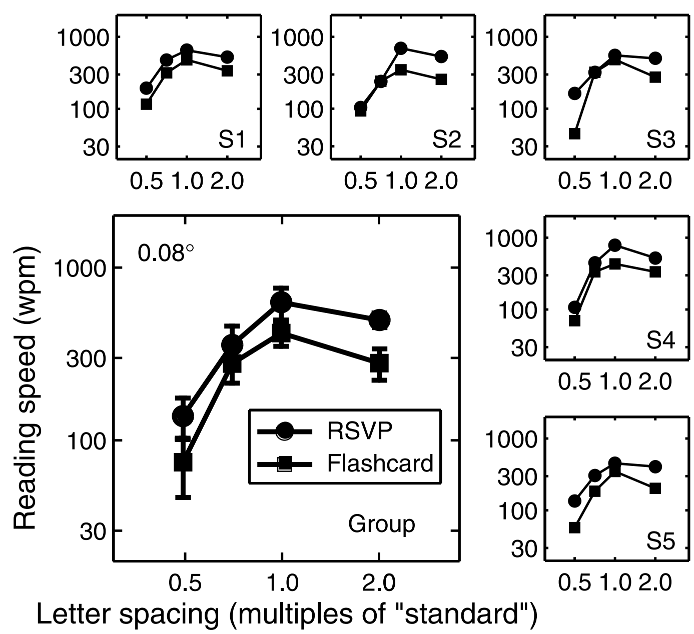

Figure 3. RSVP and flashcard reading speeds (in words per minute, wpm) as a function of letter spacing for the five individual participants and for the group average for the smaller print size of 0.08°. The error bar for the group data shows ±1 *SD*.

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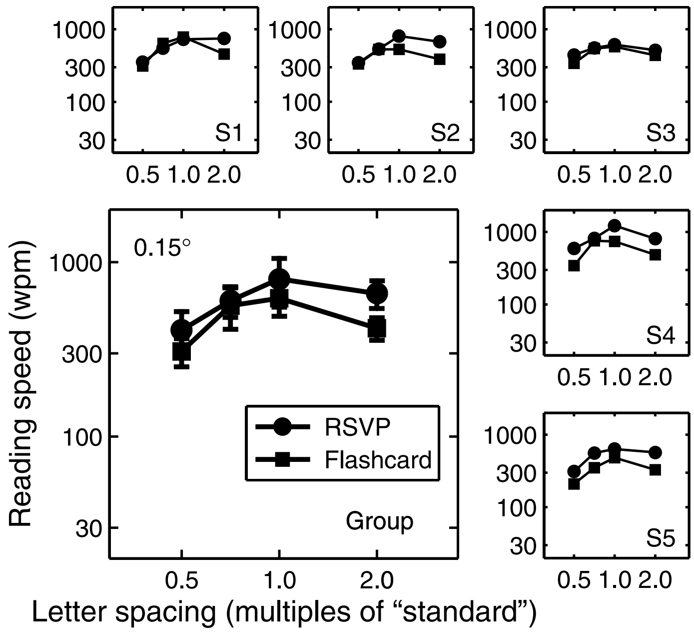

Figure 4. RSVP and flashcard reading speeds (in words per minute, wpm) as a function of letter spacing for the five individual participants and for the group average for the larger print size of 0.15°. The error bar for the group data shows ±1 *SD*.

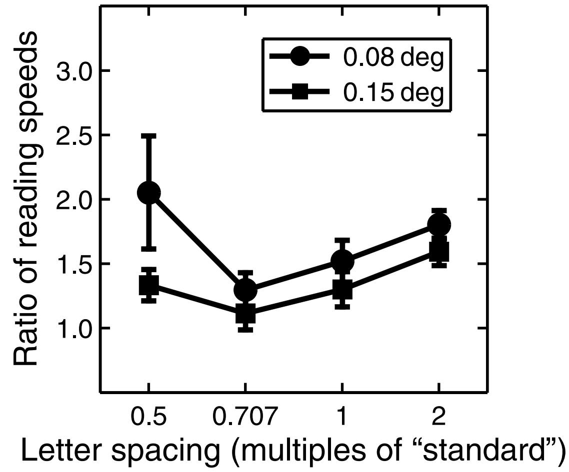

Figure 5. Ratio of RSVP reading speed to flashcard reading speed as a function of letter spacing for the two print sizes: 0.08° and 0.15°. The error bar shows ±1 *SD*.

We used a three-factor repeated measures ANOVA to analyze log reading speeds. The three factors were letter spacing (0.5×, 0.707×, 1×, and 2× standard letter spacing), presentation method (RSVP, flashcard), and print size (0.08°, 0.15°). All three main effects were statistically significant, and there were two significant interaction effects—presentation method × print size and letter spacing × print size. The three-way interaction effect among presentation method, print size, and letter spacing on reading speed was not significant.

Across print sizes and presentation methods, reading speed changes with letter spacing, $F(3,12) = 305.46$, $p < .0005$. As shown in Figures 3 and 4, reading speed increased with letter spacing and reached the maximum near the standard letter spacing. A further increase of letter spacing produced a slight decrease in reading speed. Chung (2002) found that reading speed was slower at 2× standard spacing than at the standard spacing in the fovea. Figures 3 and 4 confirm this finding for both RSVP, $t(4) = 3.86$, one tailed, $p = .009$ (for 0.08°) and $t(4) = 2.36$, one tailed, $p = .039$ (for 0.15°), and flashcard reading, $t(4) = 6.58$, one tailed, $p = .0014$ (for 0.08°) and $t(4) = 8.53$, one tailed, $p = .0005$ (for 0.15°). This decrease in reading speed was consistent across all participants and averaged about 25%.

We expected and found that reading speeds were faster for RSVP than flashcard presentation, $F(1,4) = 68.31$, $p = .001$. Collapsed across print size and spacing, the ratio of RSVP to flashcard reading speed averaged 1.44. Other studies have typically found a larger difference between RSVP reading speed and eye-movement-based reading speed. For instance, Juola, Ward, and McNamara (1982) found that RSVP reading speed was twice that for page reading at a given comprehension level.

Reading speeds were also faster for the larger print size than for the smaller print size, $F(1,4) = 123.32$, $p < .0005$, across presentation method and spacing. The ratio of the reading speed at large print size to the one at small print size averaged 1.88.

The interaction between presentation method and print size is significant, $F(1,4) = 9.94$, $p = .034$. Figure 5 shows that the speed differences between RSVP and flashcard reading were greater at the smaller print size (0.08°) than at the larger print size (0.15°).

There was also a significant interaction between letter spacing and print size, $F(3,12) = 30.36$, $p < .0005$. From the curves shown in Figures 3 and 4, reading speed increases more rapidly with letter spacing at the small print size than at the large print size before reading speed reaches the maximum. This pattern was also found by Chung (2002) and is consistent with our third prediction.

Visual-span profiles at different letter spacings

Visual-span profiles for the two print sizes are plotted in Figures 6 and 7. The peaks of all the profiles occur near letter position 0, and the right sides of the profiles are slightly broader than the left. As spacing increases from the minimum value, the peaks of the profiles get higher. The peaks of the fitted curves at the standard letter spacing averaged 0.83 ± 0.07 (*SD*) for small print size (0.08°) and 0.98 ± 0.02 for large print size (0.15°).

We predicted that the visual-span size would have the same dependence on letter spacing as reading speed. If so, we would expect the size of the visual span to decrease from the standard spacing to 2× the standard spacing

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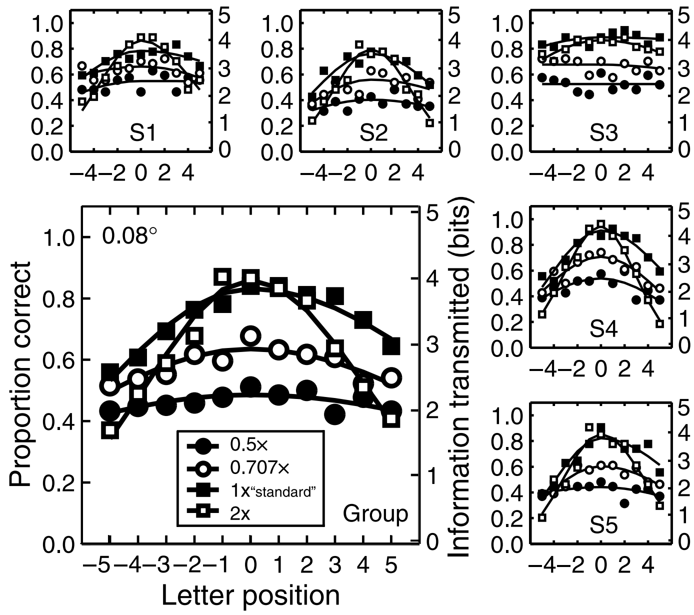

Figure 6. Visual-span profiles are shown for four spacing conditions for the smaller print size of 0.08°. The profiles consist of plots of letter-recognition accuracy (based on trials in the trigram test) as a function of letter position. Data from each condition are fitted with split Gaussians. Profiles are shown for the five individual participants and for the group average.

because we found a decrease in reading speed across these two spacing conditions.

Our measure for the size of the visual span is the information in bits summed across the 11 letter slots in the visual-span profile (see the Procedures and data analysis section). Figures 8 and 9 show the size of the visual span as a function of letter spacing for the smaller and larger print sizes. A two-factor (print size and letter spacing) repeated measures ANOVA was used to analyze the data on the visual-span size. Both main effects and the interaction effect were statistically significant.

From the analyses, the size of the visual span changes with letter spacing, $F(3,12) = 86.82$, $p < .0005$. Figures 8 and 9 clearly show that, like reading speed, visual-span size increases with letter spacing initially, up to the standard spacing, and then decreases at 2× standard spacing, which is consistent with our first prediction. The largest visual spans (37.4 ± 4.5 bits for small print size; 45.5 ± 2.4 bits for large print size) were obtained at the standard spacing. The decrease of information transmitted between the standard spacing and twice the standard spacing is statistically significant, $t(4) = 5.73$, one tailed, $p = .0023$ (for 0.08°) and $t(4) = 5.04$, one tailed, $p = .0036$ (for 0.15°). It is interesting to note that although the size of the visual span decreased from the standard spacing to 2× spacing, the peaks of the profiles are actually slightly

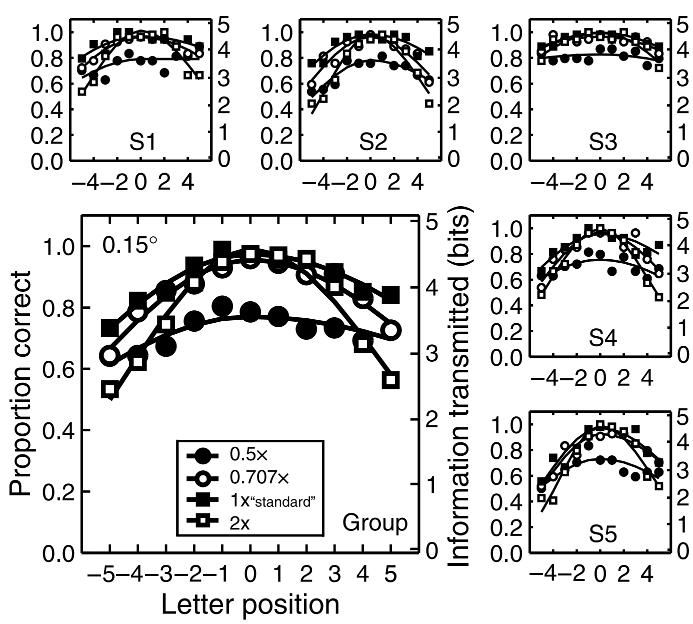

Figure 7. Visual-span profiles are shown for four spacing conditions for the larger print size of 0.15°. The profiles consist of plots of letter-recognition accuracy (based on trials in the trigram test) as a function of letter position. Data from each condition are fitted with split Gaussians. Profiles are shown for the five individual participants and for the group average.

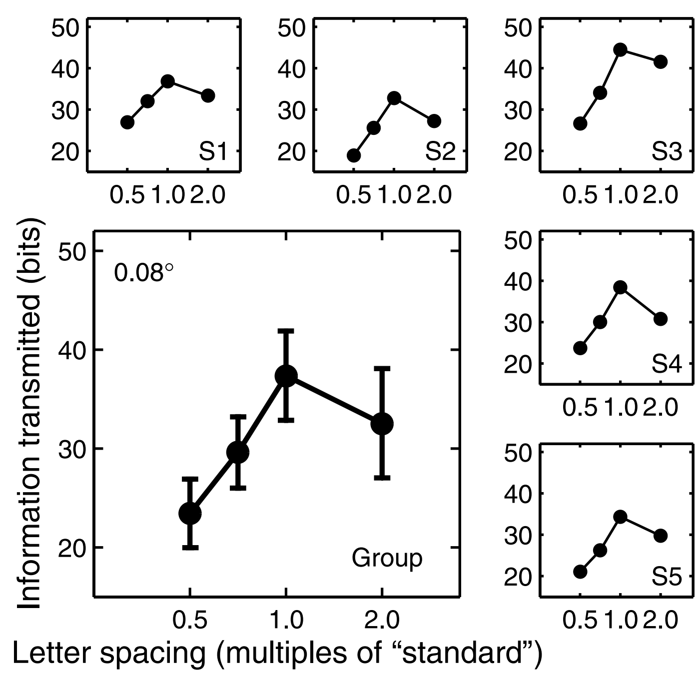

Figure 8. Size of the visual span (bits of information transmitted) is plotted as a function of letter spacing for the smaller print size of 0.08°. Five small panels show the data from the five individual participants, and the large panel shows the group average. The error bar shows ±1 *SD*. The information transmitted was calculated by summing across 11 letter positions.

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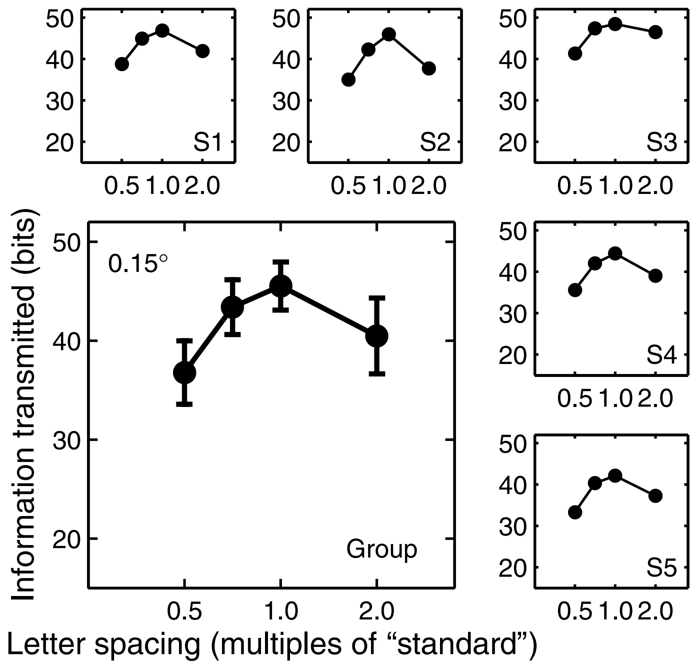

Figure 9. Size of the visual span (bits of information transmitted) is plotted as a function of letter spacing for the larger print size of 0.15°. Five small panels show the data from the five individual participants, and the large panel shows the group average. The error bar shows ±1 *SD*. The information transmitted was calculated by summing across 11 letter positions.

higher for 2× spacing (0.87 ± 0.05 for small print size and 1.00 ± 0.01 for large print size) than for the standard spacing. Putting it another way, letter recognition on the midline is slightly higher for the 2× spacing condition, although reading speed and the size of the visual span are reduced. Because reading speeds are also slower at 2× standard spacing, it appears that reading speed is more closely linked to the visual-span size (measured in bits of information transmitted) than to the peak amplitude of the profile.

Visual spans were larger for the larger print size of 0.15°, $F(1,4) = 156.55$, $p < .0005$. The difference in information transmitted between print size 0.15° and 0.08° averaged 10.82 bits.

We also found a significant interaction between letter spacing and print size, $F(3,12) = 18.01$, $p < .0005$, which is consistent with our third prediction. Figures 8 and 9 show that visual-span size had a steeper increase at the smaller print size when letter spacing ranged from 0.5× to 1× standard spacing.

Correlation between reading speed and the size of the visual span

To test our primary hypothesis that the dependence of reading speed on spacing is related to the size of the visual span, we determined the correlation between log reading speed and the size of the visual span (measured as the number of bits transmitted). This is actually a correlation between two log measures because information transmitted in bits is a logarithmic quantity. In Figure 10, log reading speed is plotted as a function of visual-span size, and the correlation coefficients were calculated for RSVP and flashcard reading, respectively.

Figure 10 shows that both RSVP and flashcard reading speeds have strong correlations with visual-span size, with the correlation between visual-span size and reading speed accounting for between 53.1% and 93.9% of the variance in reading speeds. These results address our secondary

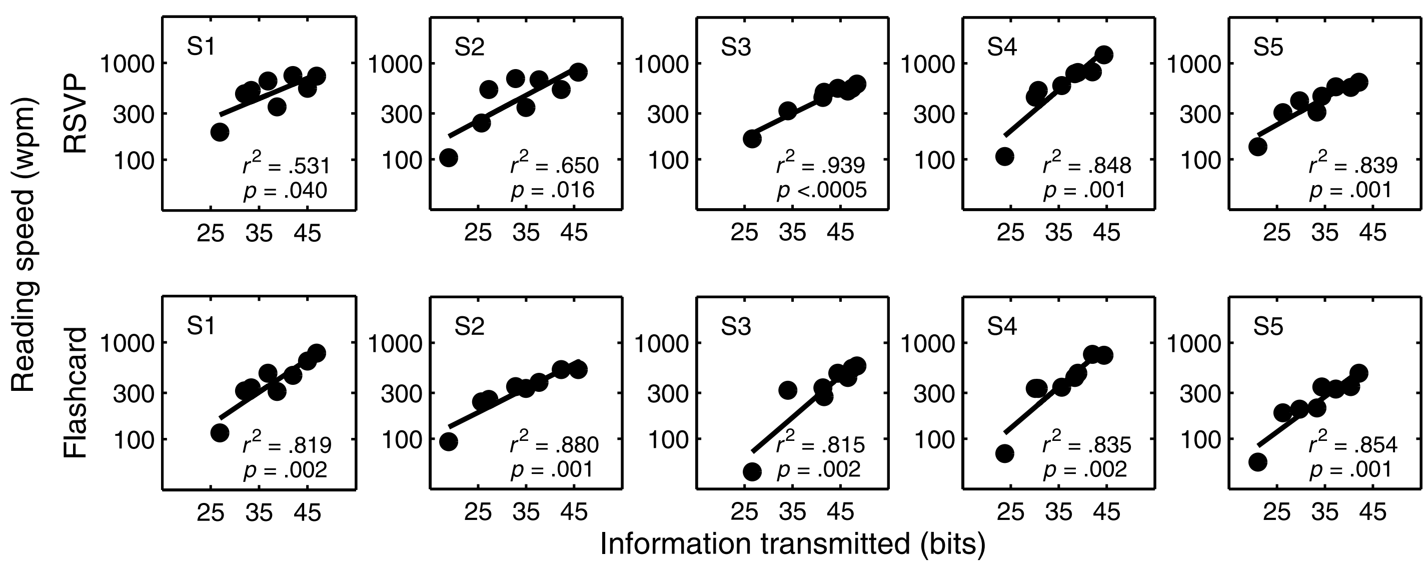

Figure 10. Scatter plot showing the correlation between log reading speed and the size of the visual span (information transmitted across the central 11 slots) for each participant. Each point represents the reading speed and the corresponding visual-span size for one spacing and one print size. Each panel includes data from both print sizes (0.08° and 0.15°) and four letter spacings (0.5×, 0.707×, 1×, and 2× standard letter spacing). The top and bottom rows show data obtained using the RSVP paradigm and the flashcard method, respectively.

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goal by showing that the strong association between RSVP reading speed and size of the visual span generalizes to reading with eye movements.

Discussion and conclusions

We found that visual-span size and reading speed had the same qualitative dependence on letter spacing and that they were highly correlated. This is consistent with the hypothesis that the size of the visual span is a front-end visual factor that limits reading speed. We now return to a question asked at the beginning of this paper—why does reading speed decrease for extrawide spacing, despite a likely reduction in crowding? Our answer, derived from our hypothesis, is that the size of the visual span decreases for extrawide spacing, resulting in a corresponding reduction in reading speed. But why does the visual span decrease in size for extrawide spacing? Presumably, the advantage due to decreased crowding between letters is more than offset by the disadvantages of placing the more widely spaced letters farther from the midline, for example, reduction of spatial resolution and greater positional uncertainty. These competing factors (reduced crowding vs. poorer spatial resolution and position coding) have a net effect of reducing the size of the visual span for reading.

Our results clearly demonstrate that the correlation between reading speed and visual-span size generalizes from RSVP reading to reading with eye movements. There are theoretical reasons to expect this generalization. Legge, Klitz, et al. (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 into account reading time or speed, a reduction in mean saccade length would normally be indicative of a reduced reading speed.

What about the effect of print size? Arditi et al. (1990) found that crowding is stronger near the acuity limit. This finding led us to expect that we would find stronger effects of letter spacing on both reading speed and visual span for a very small print size. This is what we found. We used two print sizes in this study: one smaller and one larger than the CPS. We found that both visual-span size and reading speed had a stronger dependence on spacing for the smaller print size.

The nonmonotonic dependence of both visual span and reading speed on spacing indicates that neither crowding by itself nor the effect of retinal eccentricity by itself can account for our findings. Our findings of decreased reading speed and visual span at extrawide spacing, despite a presumptive reduction in crowding, rule out crowding as the sole limiting factor on reading speed. Similarly, the growth in reading speed and in the size of the visual span for increasing spacing below the peak value rules out retinal eccentricity as the sole limiting factor. As further evidence against retinal eccentricity being the primary factor, replotting visual-span profiles as a function of retinal eccentricity, rather than as a function of letter position, does not result in superposition of the profiles. Clearly, some trade-off of the underlying sensory factors—likely including crowding, spatial resolution, and positional uncertainty—accounts for the nonmonotonic curves we obtained. Our quantification of these factors through the intermediate-level construct of the visual span provides a compact way to describe the impact of sensory factors on reading speed.

We summarize our findings with four conclusions: (1) The high correlation between reading speed and size of the visual span is consistent with the hypothesis that spacing effects on reading speed are due to changes in the size of the visual span. (2) In particular, there is a nonmonotonic change in both reading speed and size of the visual span with letter spacing such that for extrawide spacing, reading speed becomes slower and the size of the visual span becomes smaller. (3) The greater impact of spacing on reading speed near the acuity limit is due to a corresponding greater impact on the size of the visual span. (4) The high correlation between the size of the visual span and reading speed generalizes from RSVP reading to reading with eye movements.

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