



Spatial-frequency requirements for reading revisited

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ABSTRACT

Blur is one of many visual factors that can limit reading in both normal and low vision. Legge et al. [Legge, G. E., Pelli, D. G., Rubin, G. S., & Schleske, M. M. (1985). Psychophysics of reading. I. Normal vision. *Vision Research*, 25, 239–252.] measured reading speed for text that was low-pass filtered with a range of cutoff spatial frequencies. Above 2 cycles per letter (CPL) reading speed was constant at its maximum level, but decreased rapidly for lower cutoff frequencies. It remains unknown why the critical cutoff for reading speed is near 2 CPL. The goal of the current study was to ask whether the spatial-frequency requirement for rapid reading is related to the effects of cutoff frequency on letter recognition and the size of the visual span. Visual span profiles were measured by asking subjects to recognize letters in trigrams (random strings of three letters) flashed for 150 ms at varying letter positions left and right of the fixation point. Reading speed was measured with Rapid Serial Visual Presentation (RSVP). The size of the visual span and reading speed were measured for low-pass filtered stimuli with cutoff frequencies from 0.8 to 8 CPL. Low-pass letter recognition data, obtained under similar testing conditions, were available from our previous study (Kwon & Legge, 2011). We found that the spatial-frequency requirement for reading is very similar to the spatial-frequency requirements for the size of the visual span and single letter recognition. The critical cutoff frequencies for reading speed, the size of the visual span and a contrast-invariant measure of letter recognition were all near 1.4 CPL, which is lower than the previous estimate of 2 CPL for reading speed. Although correlational in nature, these results are consistent with the hypothesis that the size of the visual span is closely linked to reading speed.

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1. Introduction

Reading is a complex task involving higher cognitive and linguistic processing. Yet, when front-end visual processing is inadequate due to external environmental factors (e.g., excessive viewing distance or dim lighting), refractive error, or other visual impairments, people often have difficulty in reading. Blur is a visual factor that can limit reading in normal vision and plays a role in several forms of low vision, e.g., cataract, and corneal scarring. Blur usually refers to the attenuation or elimination of the high-frequency content of images quantified as low-pass spatial-frequency filtering.

Legge et al. (1985) measured reading speed for text that was low-pass filtered with a range of cutoff spatial frequencies. Above 2 cycles per letter (CPL) reading speed was constant at its maximum level. For cutoff frequencies below 2 CPL, reading speed decreased rapidly. It is, however, not known why the critical bandwidth (i.e., critical cutoff frequency) for reading speed is near 2 CPL.

Letters are the fundamental building blocks of text. There is compelling evidence that word recognition relies on prior letter recognition (Pelli, Farell, & Moore, 2003). If letter recognition is necessary for reading text, it is reasonable to hypothesize that the critical cutoff for reading is determined by the critical cutoff for recognizing letters. In our previous study (Kwon & Legge, 2011), we found that a high level of letter-recognition accuracy (80%) is possible when letters are low-pass filtered with a cutoff frequency of 0.9 CPL. Near 1.1 CPL, letter recognition accuracy was close to 100%. These results show that the critical cutoff for recognizing letters is substantially lower than the previously reported critical cutoff of 2 CPL for reading. This discrepancy in cutoff values might be due to methodological differences between the two studies such as filtering techniques. Or it might be due to a difference in spatial-frequency cutoff requirements for single letter recognition and reading. This discrepancy motivated us to revisit the spatial-frequency requirements for reading in the current study by measuring reading speed in a more comparable manner to our previous single letter recognition study (Kwon & Legge, 2011). Thus, the goal of the current study was to examine the relationship between letter recognition and reading speed using the manipulation of spatial-frequency cutoff.

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In another study (Kwon, 2010), we observed a new property of letter recognition that may be relevant to the proposed linkage to reading speed. Under conditions of severe blur, the human visual system requires more contrast to recognize letters. The increased requirement for suprathreshold contrast in letter recognition occurs for cutoffs below 1.47 CPL. It implies that there are two distinct critical cutoffs for single letter recognition—a critical cutoff of about 0.9 CPL for contrast-dependent letter recognition, and a critical cutoff of 1.47 CPL for contrast-independent letter recognition.

Letter recognition by itself may not be sufficient to characterize the perceptual front end of reading. If letter recognition were the only critical perceptual factor, we might expect that as soon as letters exceed 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. For instance, the minimum print size allowing for maximum reading speed (termed “critical print size”) in central vision is approximately 0.2 deg (Chung, Mansfield, & Legge, 1998; Legge & Bigelow, 2011; Legge et al., 1985), roughly three times larger than the acuity limit. The minimum contrast allowing for maximum reading speed is between about 5% and 10% Michelson contrast (Legge et al., 1990; Legge, Rubin, & Luebker, 1987), which is three to six times the threshold contrast for letter recognition. It has been proposed that the visual span, the number of letters that can be recognized without moving the eyes, imposes an additional limitation on reading speed (Legge, Mansfield, & Chung, 2001). The visual span can be thought of as the size of a window in the visual field within which letters can be recognized reliably.

The visual-span hypothesis predicts correlated changes in reading speed and the size of the visual span. There has been accumulating evidence for this correlation. For adults with normal vision, manipulation of several text properties produces highly correlated changes in reading speed and the size of the visual span; these text properties include letter contrast and size (Legge et al., 2007), letter spacing (Yu et al., 2007), text oriented horizontally or vertically (Yu et al., 2010) and retinal eccentricity (Legge, Mansfield, & Chung, 2001). The correspondence between changes in reading speed and the size of the visual span has also been observed in the reading development of English-speaking children (Kwon, Legge, & Dubbels, 2007) and French-speaking children (Dubois & Valdois, 2010).

Pelli et al. (2007) have shown that a similar concept, which they termed “uncrowded span”, is directly linked to reading speed. The influential role of the size of the visual span in reading speed was also demonstrated in a computational model called “Mr. Chips”, which uses the size of the visual span as a key parameter (Legge, Klitz, & Tjan, 1997; Legge et al., 2002).

These empirical and theoretical findings provide convergent evidence for a linkage between reading speed and the size of the visual span. To the extent that the size of the visual span is a contributor to reading speed, we would expect to see similar cutoff-frequency dependence for the size of the visual span and reading speed.

2. Method

2.1. Subjects

Seven subjects were recruited from the University of Minnesota campus and participated in the central-vision testing. They were all native English speakers with normal or corrected-to-normal vision and normal contrast sensitivity. Mean acuity (Lighthouse distance acuity chart) was -0.11 logMAR (Snellen 20/16) ranging from -0.24 (Snellen 20/11) to 0.02 (Snellen 20/21). Mean LOG contrast sensitivity (Pelli-Robson chart) was 1.74 with a range

from 1.65 to 1.90. They participated in both trigram and reading speed tasks for the central-vision condition. A separate group of five subjects was tested in the trigram and reading speed tasks for the peripheral viewing condition; they had comparable visual acuity (-0.17 logMAR) and LOG contrast sensitivity (1.85) to the central viewing group.

Subjects were either paid \$10.00 per hour or granted class credit for their participation. The experimental protocols were approved by the Internal Review Board (IRB) at the University of Minnesota and written informed consent was obtained from all subjects.

2.2. Stimuli

2.2.1. Stimulus images

The 26 lowercase Courier font letters of the English Alphabet—a serif font with fixed width and normal spacing—were used for both visual span and reading speed tasks. The letters were black on a uniform gray background (40 cd/m²) with a contrast of 95% (for unfiltered letters). Letter size was defined as the font’s x -height of 1 deg (31 pixels) at the 60 cm viewing distance. The letter images were constructed in Adobe Photoshop (version 8.0) and MATLAB (version 7.4).

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

Oral reading speed was measured with Rapid Serial Visual Presentation (RSVP). The pool of test material consisted of 187 sentences developed for testing reading speed by Legge et al. (1989). All the sentences were 56 characters in length. The mean word length was 3.7 letters and 93% of the 1581 unique words occur in the 2000 most frequent words based on The Educator’s Word Frequency Guide (Zeno et al., 1995). Mean difficulty of the sentences in the pool was 4.77 (Gunning’s Fog Index), and 1.34 (Flesh-Kincaid Index). According to Carver’s (1976) formula,¹ the mean difficulty level is below 2nd grade level. Allowing for differences in these metrics, the difficulty of the sentences is roughly 2nd to 4th grade level. We divided the sentence pool into two sub-pools, so that there were separate, non-overlapping sets of sentences for RSVP and practice. Sentences were selected randomly without replacement, so that no subject saw the same sentence more than once during testing.

2.2.2. Image filtering

The images were blurred using a third order Butterworth low-pass filter in the spatial frequency domain. The cutoff frequency of the filter (in cycles per letter, CPL) ranged from 0.8 to 8 CPL depending on task and stimulus conditions. The filter function is

$$f = \frac{1}{\left(1 + \left(\frac{r}{c}\right)^{2n}\right)} \quad (1)$$

where r is the radial frequency, c is the low-pass cut-off radial frequency and n is the filter’s order.

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

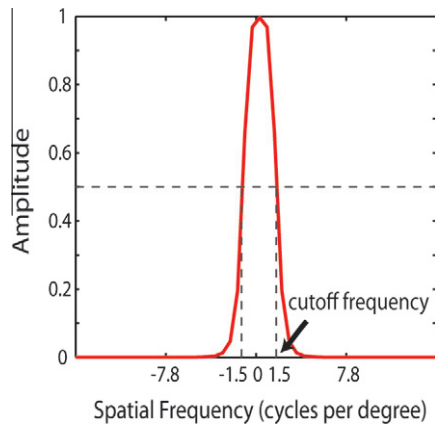


Fig. 1. The response function of the 3rd order Butterworth filter with the cut-off frequency of 1.5 cycles per degree (CPD), equivalent to 1.5 cycles per letter for a 1° letter size.

The filter's response function is shown in Fig. 1. Fig. 2 provides samples of low-pass filtered and unfiltered images. In our study, words and trigrams were low-pass filtered as whole images.

2.2.3. Image display on screen

To present the filtered images on the monitor, we mapped the luminance values of the image pixels to the 256 gray levels. The DC component value (i.e., the average value of the signal) of the filtered image was mapped to the gray level of 127, equivalent to the mean luminance of the monitor (40 cd/m²). The stimuli were generated and controlled using MATLAB (version 7.4) and Psychophysics Toolbox extensions (Mac OS X) (Brainard, 1997; Pelli, 1997), running on a Mac Pro computer. The display was a 19" CRT monitor (refresh rate: 75 Hz; resolution: 1152 × 870). Luminance of the display monitor was made linear using an 8-bit look-up table in conjunction with photometric readings from a MINOLTA CS-100 Chroma Meter. The image luminance values were mapped onto the values stored in the look-up table for the display. Subjects performed all the tasks in a dark room while they were seated in a comfortable position with chin and forehead supports.

2.3. Procedure

2.3.1. Measuring visual-span profiles

Visual-span profiles were measured using a letter recognition task. Trigrams² were centered at 15 letter positions, including 0 (the letter position at fixation) and from 1 to 7 letter widths left and right of the 0 position (Fig. 3). Each of the 15 trigram positions was presented for 150 ms exposure duration and tested 15 times, in a random order, within a block of 225 trials. The task of the subject was to report the three letters from left to right. A letter was scored as being identified correctly only if its order within the trigram was also correct. Feedback was not provided to the subjects about whether or not their responses were correct.

Subjects were instructed to fixate between two vertically separated (1.5°) and horizontally oriented fixation lines (each 0.33° in height and 0.1° in width) on the computer screen during trials (this configuration allowed for presenting a trigram at fixation without superposition of the fixation marks on the middle letter of the trigram) (Fig. 3). The fixation lines were short white lines (76 cd/m², 90% contrast).

² Trigrams were used rather than isolated letters because of their closer approximation to English text. Text contains strings of letters. Most letter recognition in text involves characters flanked on the left, right or both sides.

The experimenter visually observed subjects to confirm that fixation instructions were followed. Since there was no way of predicting on which side of fixation the trigram would appear, and the exposure time was too brief to permit useful eye movements, the subjects understood that there was no advantage in deviating from the intended fixation. All subjects had practice trials prior to data collection.

Proportion correct recognition was measured at each of the letter slots and combined across the trigram trials in which the letter slot was occupied by the outer (the furthest letter from fixation), middle, or inner (the one closest to fixation) letter of a trigram. This means that although trigrams were centered at a given position only 15 times in a block, data from that position were based on 45 trials. A visual span profile consisted of percent correct letter recognition as a function of letter position left and right of fixation. These profiles were fit with 'split Gaussians', that is, Gaussian curves that are characterized with amplitude (the peak value at letter position 0), and separate estimates of left and right standard deviations (characterizing the breadth of the curve).

As illustrated by the right vertical scale in Fig. 3, percent correct letter recognition can be linearly transformed to information transmitted in bits. The information values range from 0 bits for chance accuracy of 3.8% correct (the probability of correctly guessing one of 26 letters) to 4.7 bits for 100% accuracy (Legge, Mansfield, & Chung, 2001).³ The size of the visual span was quantified by summing across the information transmitted in each slot (similar to computing the area under the visual span profile). Lower and narrower visual span profiles transmit fewer bits of information.

Visual-span profiles were obtained in both central and peripheral visual fields (10° lower visual field). Visual-span profiles were measured for each participant using trigrams that were filtered with six different cutoffs including unfiltered trigrams (0.8, 0.9, 1.05, 1.2, and 2.5 CPL for the central viewing condition; 1.25, 1.55, 2, 4, and 8 CPL for the peripheral viewing condition), one cutoff per block. The order of the six spatial-frequency cutoff conditions was counterbalanced across subjects. For the central-field testing, a post mask consisting of unfiltered x's followed the trigram. For testing in the lower visual field, the post mask was omitted because it appeared to have differential effects on filtered and unfiltered trigrams.⁴

2.3.2. Measuring RSVP reading speed

Oral reading speed was measured with Rapid Serial Visual Presentation (RSVP). The method of constant stimuli was used to present sentences at five exposure durations. Reading speed was obtained in both central and peripheral visual fields (10° lower visual field). Reading speed was measured for each subject using sentences with six different cutoffs including unfiltered sentences (0.8, 0.9, 1.05, 1.2, and 2.5 CPL for the central viewing condition; 1.25, 1.55, 2, 4, and 8 CPL for the peripheral viewing condition), one cutoff per block. The order of the six spatial-frequency cutoff conditions was counterbalanced across subjects.

During the testing session, the range of exposure durations for each subject was chosen in order to make sure that at least 90% correct response (percent of words read correctly in a sentence) was obtained at the longest exposure time. For RSVP, the sentences were presented sequentially one word at a time at the same screen location (i.e., the first letter of each word occurred at the same

³ Percent correct letter recognition was converted to bits of information using letter-confusion matrices by Beckmann (1998).

⁴ Subjects had particular difficulty carrying out the letter-recognition task in peripheral vision when the filtered letters were masked by unfiltered x's, i.e., there was a substantially greater impact on performance with filtered compared with unfiltered letters. Because we did not understand the basis for this difference, we decided not to use the mask for the peripheral viewing condition.

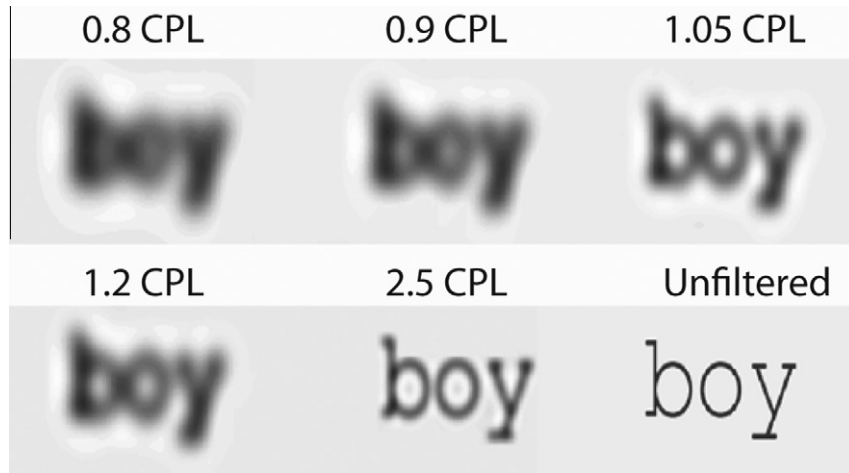


Fig. 2. Samples of low-pass filtered and unfiltered images.

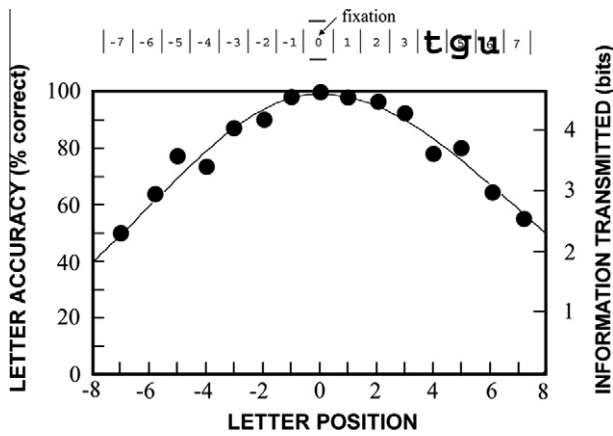


Fig. 3. Visual span profile. Top: Trials consisted of the presentation of trigrams, random strings of three letters, at specified letter positions left and right of fixation. Bottom: Example of a visual-span profile, in which letter recognition accuracy (% correct) is plotted as a function of letter position for data accumulated across a block of trials. The right vertical scale shows the transformation from accuracy to information transmitted in bits. The size of the visual span is the sum of the information transmitted in bits across the letter positions.

screen location). There was no blank frame (inter-stimulus interval) between words. Each sentence was preceded and followed by strings of x's as shown in Fig. 4.

Subjects initiated each trial by pressing a key. They were instructed to read the sentences aloud as quickly and accurately as possible. But, subjects were allowed to correct their verbal response after the stimulus presentation. A word was scored as correct, even if given out of order, e.g., a correction at the end of a sentence, the number of words read correctly per sentence was recorded. Four sentences were tested for each exposure duration and percent correct word recognition was computed at each exposure time.

Psychometric functions, percent correct versus RSVP exposure duration, were created by fitting these data with cumulative Gaussian functions (Wichmann & Hill, 2001) as shown in Fig. 5. Five data points in each panel represent percent words read correctly in a sentence. The threshold exposure duration, for words of a given length was based on the 80% correct point on the psychometric function. For example, if an exposure time of 200 ms per word yielded 80% correct, the reading rate was five words per second, equals to 300 words per minute (wpm).

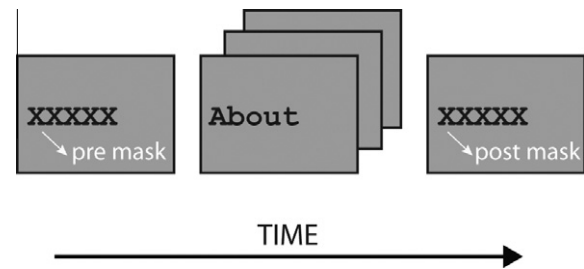


Fig. 4. A schematic diagram of the RSVP reading speed task.

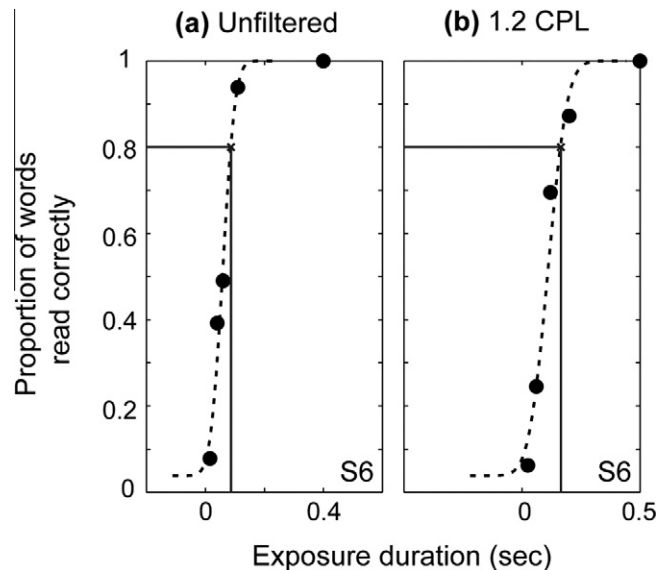


Fig. 5. Proportion of words read correctly is plotted as a function of exposure duration (s) per word (subject 6) from unfiltered (a) and 1.2 CPL cutoff conditions (b). Each set of data was fit with a cumulative Gaussian function. From each psychometric function, the threshold exposure duration was defined as the exposure duration yielding 80% of words read correctly.

2.3.3. Estimating critical cutoff

Similar to Legge et al. (1985), we fitted the graphs of reading speed (or visual span) vs. cutoff frequency by a two-limbed function (Eq. (2)), containing a rising straight line and a horizontal

straight line. Such two-limbed fits allow us to summarize the graph by the coordinates of the point of intersection of the two lines. The *X*-coordinate of this point is called the *critical cutoff*. The *Y*-coordinate is called the *maximum reading speed or visual span*. The critical cutoff is the minimum cutoff required for maximum reading speed or visual span size.

$$Y = b, \quad \text{if } X \geq c$$

$$Y = a * X + b - a * c, \quad \text{if } X < c \quad (2)$$

where *Y* is reading speed or visual span, *X* is spatial-frequency cutoff and *a*, *b*, *c* are free parameters.

3. Results

3.1. The effects of cutoff frequency on the size of the visual span

Fig. 6 shows group mean visual span profiles for six cutoff frequencies in central vision (panel a) and peripheral vision (panel b). For both cases, as cutoff frequency increased, the peak values of the profiles became larger. Consistent with earlier studies (Legge, Mansfield, & Chung, 2001; Legge et al., 2007), the peak values of the profiles in peripheral vision were smaller than those in central vision for the same cutoff frequency condition. For example, the peak value of the profile for the unfiltered condition in central vision was 97% while the peak value in the periphery was 80%.

The size of the visual span was quantified as bits of information transmitted (see Section 2). We conducted a separate ANOVA analysis on central and peripheral data because different cutoff frequencies and different groups of subjects were used for central and peripheral viewing conditions.

First, we performed an analysis of variance (ANOVA) on visual span size (bits) for central vision—one way repeated measures ANOVA with cutoff frequency as a within-subject factor. There was a significant main effect of cutoff frequency on visual span size ($F_{(5,30)} = 188.99, p < 0.001$). As shown in Fig. 6, the visual span size in central vision increased with increasing cutoff frequency up to the cutoff frequency of 2.5 CPL. There was no significant difference in the size of the visual span for the 2.5 CPL (56.82 bits \pm 1.25) and for the unfiltered condition (56.54 bits \pm 1.26) ($p = 0.32$).

Second, we performed an ANOVA on visual span size (bits) for peripheral vision—one way repeated measures ANOVA with cutoff frequency as a within-subject factor. There was a significant main effect of cutoff frequency on visual span size ($F_{(5,20)} = 20.54, p < 0.0001$). As shown in Fig. 6, the visual span size in peripheral vision increased with increasing cutoff frequency up to the cutoff frequency of 2 CPL. There was no significant difference in the size of

the visual span for the cutoff frequencies above 2 CPL including the unfiltered condition ($p = 0.95$), suggesting that the size of the visual span remains constant above the cutoff frequency of 2 CPL.

To estimate the critical cutoff allowing for the maximum visual span size, visual span data were fitted with the two-limbed model (Fig. 7). The fitting was performed on both group average data and each subject's data. Representative data from two individual subjects are shown (Fig. 7b and c). The parameter values from the fit with group average data were fairly consistent with the average parameter values from individual fits. In central vision, the average critical cutoff for the size of the visual span was 1.37 CPL (± 0.03) and the corresponding maximum visual span size was 56.68 bits (± 1.06). In peripheral vision, we observed a significantly larger critical cutoff frequency (2.03 ± 0.21), 48% larger than the value in central vision ($p < 0.005$) with corresponding maximum visual span size of 47.57 bits (± 5.15). These results indicate that in order to achieve maximum visual span size, the spatial frequency spectra of letters need to contain at least 1.37 CPL for central vision and 2.03 CPL for peripheral vision. Above these critical cutoffs, the size of the visual span is independent of the cutoff spatial frequency.

3.2. The effects of cutoff frequency on RSVP reading speed

Fig. 8 shows plots of RSVP reading speed in words per minute (wpm) as a function of cutoff frequency from central (closed circles) and peripheral (open circles) vision. Similar to the visual span size, reading speed increased rapidly with increasing cutoff frequency.

In central vision, RSVP reading speed increased by a factor of 6.8 from the cutoff frequency of 0.8 CPL (116.11 wpm \pm 22.61) to the cutoff frequency of 2.5 CPL (789.82 wpm \pm 89.87). Reading speed was not significantly different for 2.5 CPL and the unfiltered condition (830.95 wpm \pm 53.56) ($p = 0.57$). Consistent with many earlier studies (e.g., Chung, Mansfield, & Legge, 1998), reading speed in peripheral vision was significantly slower than central vision across all cutoffs. In peripheral vision, RSVP reading speed increased by a factor of 2.5 from the cutoff of 1.25 CPL (49.78 wpm \pm 10.65) to the cutoff frequency of 2 CPL (126.89 wpm \pm 9.9). No significant increase was shown for cutoffs above 2 CPL ($p = 0.17$).

To estimate critical cutoffs for reading, reading speed data were fitted with the two-limbed model (Fig. 8). The fitting was performed on both group average data and each subject's data. Representative data from two individual subjects are shown (Fig. 8b and c). The parameter values from the fit with group average data were fairly consistent with the average parameter values from individual

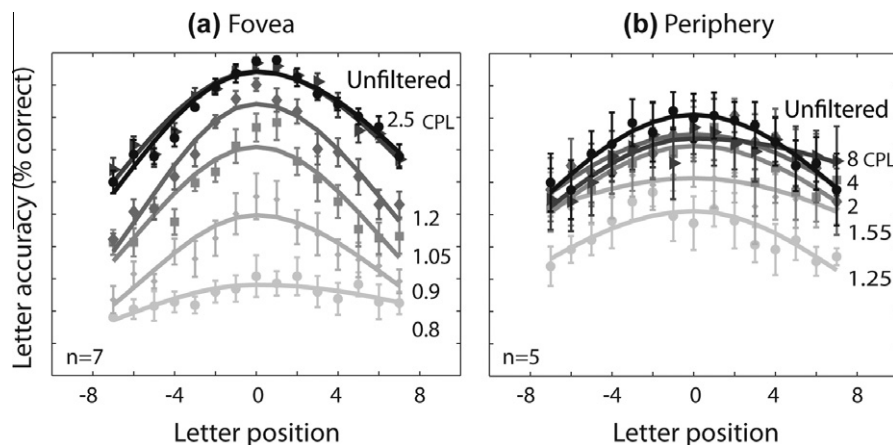


Fig. 6. Mean visual span profiles for the group of subjects as a function of cutoff frequency in central vision (a) and peripheral vision (b). Error bars represent ± 1 SEM.

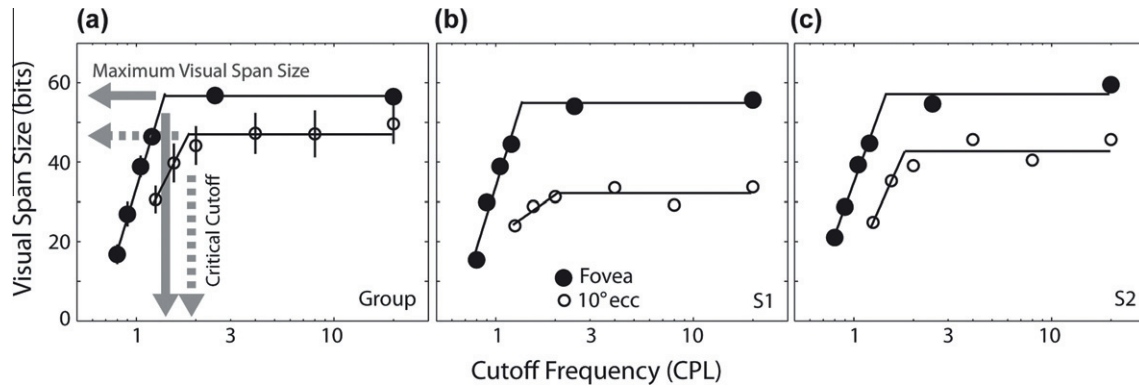


Fig. 7. Mean visual span size (bits) as a function of cutoff frequency in central vision (closed circles) and peripheral vision (open circles): (a) group average data in central ($n = 7$) and peripheral vision ($n = 5$); (b) data from subject 1; (c) data from subject 2. Error bars represent ± 1 SEM. Data were fitted with the two-limbed function. The horizontal line indicates the estimated maximum visual span size. The arrows indicate estimated critical cutoffs for the size of the visual span. Note that data for the unfiltered letters were plotted at 20 CPL, the value slightly above the highest frequency available for letters with an x-height of 31 pixels.

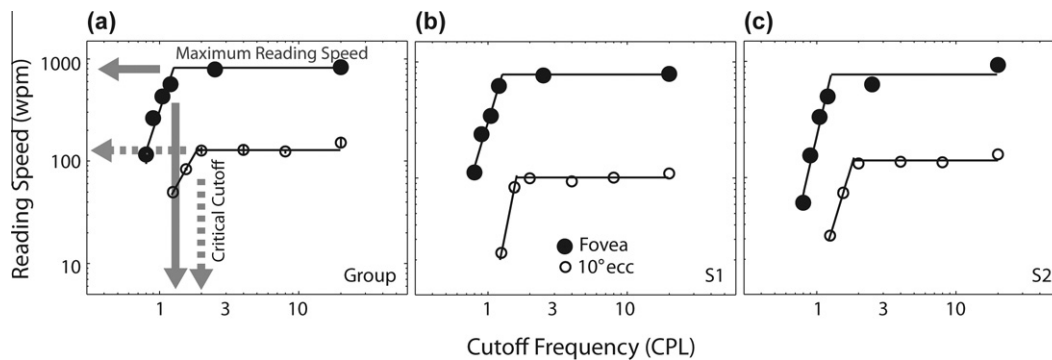


Fig. 8. Mean RSVP reading speed (wpm) as a function of cutoff frequency: (a) group average data in central ($n = 7$) and peripheral vision ($n = 5$); (b) data from subject 1; (c) data from subject 2. Error bars represent 1 SEM. Data were fitted with the two-limbed model. The horizontal line indicates the estimated maximum reading speed. The arrows indicate estimated critical cutoffs for reading speed.

fits. The average critical cutoff for RSVP reading speed in central vision was 1.34 CPL (± 0.04) and the corresponding maximum RSVP reading speed was 802 wpm (± 66.51). In peripheral vision, we observed a significantly larger critical cutoff frequency (1.94 ± 0.14), which is 45% larger than the critical cutoff in central vision ($p < 0.0001$).

These results show that in order to achieve maximum RSVP reading speed, the spatial frequency spectra of letters need to contain at least 1.34 CPL in central vision and 1.94 CPL in peripheral vision. Above these critical cutoffs, RSVP reading speed is independent of cutoff frequency. Notice that these values are very close to the critical cutoffs for the visual span, 1.37 CPL for central vision and 2.03 CPL for peripheral vision (see Fig. 7).

Our critical cutoff frequency for central reading speed, 1.34 CPL was smaller than the previously reported estimate, 2 CPL (Legge et al., 1985). This discrepancy may be due to methodological differences between the two studies. We will return to this issue in Section 4.

3.3. Relationship between the size of the visual span and RSVP reading speed

As predicted by the visual-span hypothesis, there is a close correspondence between the size of the visual span and reading speed. We conducted a regression analysis to explore this relationship further. Fig. 9 shows the regression of log RSVP reading speed (wpm) on size of the visual span (bits) for central (closed circles) and peripheral (open circles) vision. Representative data from

two individual subjects are shown (Fig. 9b and c). For central vision, we obtained a mean correlation coefficient across regressions for seven separate subjects of $r = 0.96$ (± 0.02) and $r^2 = 0.92$ (± 0.05) ($p < 0.05$). This means that 92% of the variance in RSVP reading speed data can be accounted for by the size of the visual span. We obtained the following regression equation:

$$\log_{10} \text{ RSVP Reading Speed}_{\text{fovea}} = 0.02 * \text{Visual Span (bits)} + 1.76,$$

This means that adding 4.7 bits to the size of the visual span (equivalent to one extra perfectly recognized letter) increases reading speed by 0.094 log units (i.e., a 24% increase in reading speed). Our estimated slope of the regression line, 0.02 falls into the range of slopes found in Legge et al.'s (2007) study. They showed that the average slope ranges from 0.02 to 0.04 across different studies linking the size of the visual span to reading speed.

For peripheral vision, we obtained a mean correlation coefficient across regressions for five separate subjects of $r = 0.91$ (± 0.02) and $r^2 = 0.82$ (± 0.05) ($p < 0.05$). This means that 82% of the variance in RSVP reading speed data can be accounted for by the size of the visual span. We obtained the following regression equation:

$$\log_{10} \text{ RSVP Reading Speed}_{\text{periphery}} = 0.025 * \text{Visual Span (bits)} + 0.92,$$

This means that adding 4.7 bits to the size of the visual span (equivalent to one extra letter) increases reading speed by 0.12 log units (i.e., a 32% increase in reading speed).

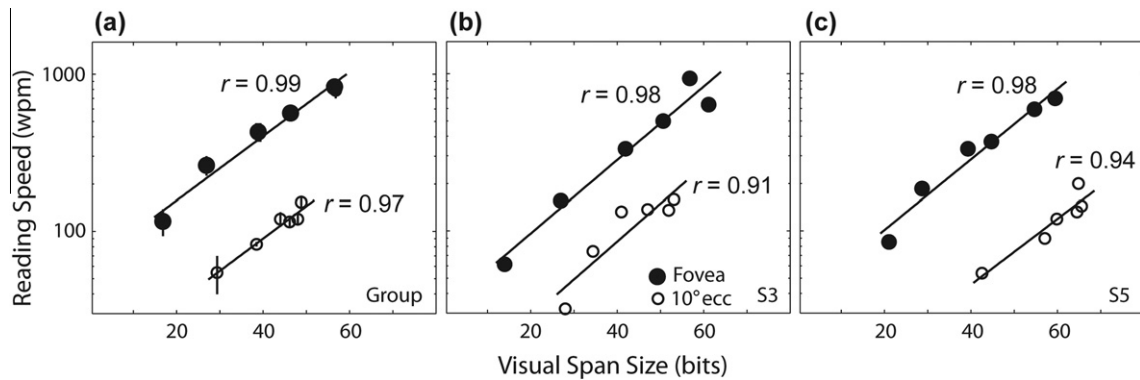


Fig. 9. Relationships between log RSVP reading speed (wpm) and the size of the visual span (bits) for central (closed circles) and peripheral (open circles) vision: (a) group average data; (b) data from subject 3; (c) data from subject 5. Error bars represent 1 SEM. The fitted lines indicate the regressions of log RSVP reading speed (wpm) on the size of the visual span (bits).

4. Discussion and conclusions

The current study found nearly identical spatial-frequency requirements for maximizing reading speed and the size of the visual span. Before considering the linkage to letter recognition, we address the discrepancy in the critical cutoff frequency for reading reported here and in the 1985 study by Legge et al.

4.1. Comparison with the cutoff frequency estimates of Legge et al. (1985)

We observed a smaller critical cutoff for reading speed (1.34 CPL) than the estimate of 2 CPL from Legge et al. (1985). This discrepancy may be due to methodological differences between the two studies. Legge et al. (1985) blurred text using a ground-glass diffuser. They modeled the blur as a Gaussian low-pass filter. Their cutoff was defined as the spatial frequency at which the MTF declined to $1/e$ (37%). On the other hand, our current study used a 3rd order Butterworth low-pass filter with the cutoff frequency defined as the frequency at half amplitude (50%). The difference in low-pass filtering technique along with different cutoff frequency criteria might contribute to the discrepancy. Another obvious methodological difference is the way reading speed was measured: RSVP reading speed in the current study vs. drifting-text reading in Legge et al. (1985). It is possible that the eye movement demands of the drifting text paradigm require a larger cutoff frequency.

To begin addressing the discrepancy in cutoff frequency estimates, we conducted a supplementary study measuring reading speeds and critical cutoffs comparing (1) Gaussian and Butterworth low-pass filtering, and (2) RSVP reading and eye-movement based reading. The eye-movement-based reading used “flashcard” text rather than drifting text, so the comparison with Legge et al. (1985) was not exact. The flashcards were short blocks of text formatted onto three lines that required saccadic eye movements. The drifting-text paradigm requires smooth-pursuit eye movements in addition to saccades. More details of the supplementary experiment are provided in Appendix A. Surprising to us, these methodological variations did not yield significant differences in the critical cutoffs for reading speed from those reported in Section 3 of this paper. Accordingly, reasons for the discrepancy in cutoff frequency estimates between the 1985 study and the present study remain unresolved. Three possibilities include differences due to (1) flashcard text vs. drifting text, (2) digital filtering vs. optical filtering with a ground-glass diffuser (possibly due to imprecise modeling of the diffuser’s characteristics by a Gaussian blur function), or (3) text characteristics such as mean word length or text difficulty.

4.2. Comparison with cutoff frequencies for letter recognition

Our results revealed a positive correlation between the size of the visual span and reading speed. In this section, we address the relationship between single letter recognition and these two variables. As mentioned in the Introduction, we previously obtained two distinct measures of critical cutoff for single letter recognition: (1) a contrast-dependent critical cutoff for letter recognition of 0.9 CPL (80% criterion); and (2) a contrast-independent critical cutoff of 1.47 CPL. The “contrast-dependent” definition refers to the requirement for high target contrast to achieve the very low critical cutoff of about 0.9 CPL. The contrast-independent definition refers to a spatial-frequency requirement which is independent of stimulus contrast down to a near-threshold value. How do these two definitions of critical cutoff for letter recognition relate to reading speed and the visual span?

The contrast-dependent critical cutoff for letter recognition of 0.9 CPL appears to be too low to account directly for the critical cutoffs near 1.4 CPL for visual span and reading speed. Could the difference be due to a criterion effect? The 0.9 CPL critical cutoff was based on an 80%-correct criterion for letter recognition, but our data (Kwon & Legge, 2011) indicate that nearly 100% correct was achieved for letters with a cutoff frequency of 1.1 CPL. The data of the present paper clearly show that reading speed and the size of the visual span are well below their maximum values at 1.2 CPL. From these considerations, we conclude that the contrast-dependent critical cutoff for single letter recognition is lower than the critical cutoffs for the visual span and reading speed.

But the contrast-independent definition of critical cutoff for letter recognition is nearly the same as the critical cutoffs for visual span and reading speed. Is it plausible to connect this second definition of critical cutoff for letter recognition with the critical cutoff for reading?

We briefly review the findings of our previous study (Kwon, 2010). We measured contrast thresholds for detecting and recognizing single letters drawn at random from the 26 lowercase letters of the English alphabet presented foveally. The letters were low-pass filtered (blurred) with various cutoffs including unfiltered letters. The gap between detection and recognition RMS contrast thresholds was quantified as the ratio of recognition to detection thresholds. We observed larger contrast ratios with decreasing spatial resolution (Kwon, 2010). The ratio increased from 1.4 for the unfiltered letters to 8.9 for the most blurred letters (0.9 CPL). The increased requirement for contrast in letter recognition occurs for cutoffs below 1.47 CPL. We designated this as the “minimum-contrast” critical cutoff for letter recognition, here termed “contrast-independent” critical cutoff. This second type of

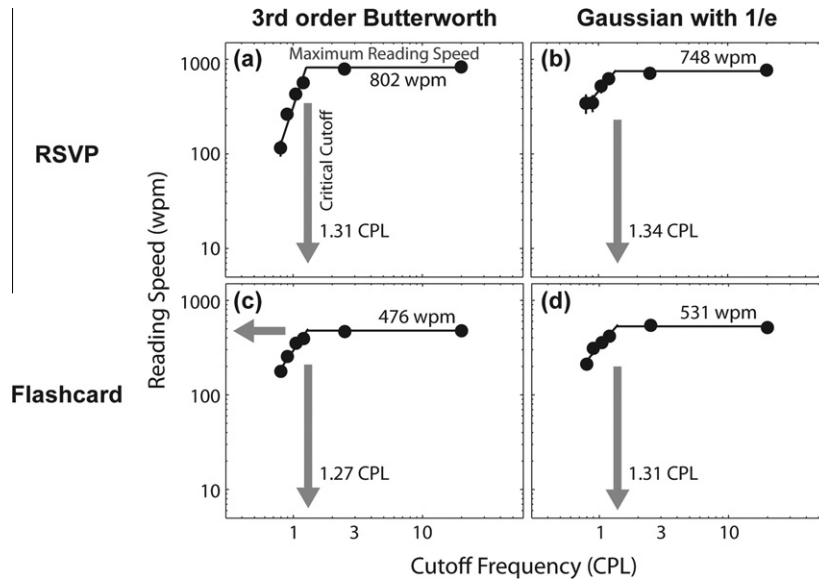


Fig. A1. RSVP reading speed (wpm) as a function of cutoff frequency for four experimental conditions: (a) RSVP reading speed with a 3rd order Butterworth filter; (b) RSVP reading speed with a Gaussian filter; (c) flashcard reading speed with a 3rd order Butterworth filter; (d) flashcard reading speed with a Gaussian filter. Group average data were fitted with the two-limbed model. The horizontal arrows indicate the estimated maximum reading speed. The vertical arrows indicate estimated critical cutoff frequencies for reading speed.

critical cutoff appears to be almost the same as the critical cutoffs for the size of the visual span and reading speed observed in the current study. A statistical analysis (ANOVA test) further confirmed that there is no significant difference among these three values ($F_{(2, 12)} = 3.25, p = 0.75$),⁵ suggesting that there is a common critical cutoff, between 1.3 CPL and 1.5 CPL for single letter recognition, the size of the visual span and reading speed. A similar pattern of results was found in peripheral vision. A common critical cutoff frequency of approximately 2 CPL was observed among the three.

The outcomes of these analyses offer us a plausible linking hypothesis between letter recognition, the size of the visual span and reading speed: Both maximum reading speed and maximum visual span appear to rely on contrast-independent letter recognition, which occurs above a cutoff frequency of 1.4 CPL. Even at somewhat lower cutoffs, people can still read and recognize letters by reverting to contrast-dependent letter recognition. It may be the case that extracting useful visual information for letter recognition below 1.47 CPL is particularly slow or perhaps more susceptible to crowding effects, resulting in a smaller visual span and slower reading speed.

In summary, we found that the size of the visual span and RSVP reading speed show a similar dependence on cutoff frequency. Both the size of the visual span and reading speed increased with increasing cutoff frequency up to the critical cutoff of approximately 1.4 CPL. Approximately 92% and 82% of the variability in RSVP reading speed were explained by the size of the visual span in central and peripheral vision respectively. Although our results are correlational in nature, they are consistent with the hypothesis that the visual span plays a limiting role in reading speed.

Comparison of these findings with our previous results on single letter recognition suggests that the spatial-frequency requirements for reading and the size of the visual span are closely linked to the spatial-frequency requirement for contrast-independent letter recognition. In other words, reading can tolerate

increasing blur until a point is reached for which letter recognition becomes sensitive to letter contrast. Under these conditions, the visual span shrinks in size and reading slows down.

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Appendix A. Effects of low-pass filter type and text-display format on critical cutoffs for reading speed

Our critical cutoff estimate for foveal reading speed, 1.34 CPL was smaller than the previously reported estimate, 2 CPL (Legge et al., 1985). We speculated that this discrepancy was due to methodological differences between the two studies. Thus, the goal of the current follow-up study was to examine whether two obvious methodological differences—types of low-pass filters and text-display formats—could account for differences in the critical cutoff for reading speed.

We measured reading speed with two display formats: Rapid Serial Visual Presentation (RSVP) and flashcard presentation. In both cases, text images were low-pass filtered with two different filters: a Gaussian low-pass filter (with cutoff frequency defined as $1/e$) corresponding to the filter used by Legge et al. (1985), and a 3rd order Butterworth filter with the cutoff frequency defined as the frequency at half amplitude (50%). Thus, we had four experimental conditions (2 filter types by 2 display formats). Seven normally-sighted subjects were randomly assigned to each condition. Each group of subjects had comparable visual acuity and contrast sensitivity.

We obtained critical cutoff frequencies for reading speed from each experimental condition by fitting data with the two-limbed model. Fig. A1 shows plots of reading speed (wpm) as a function of cutoff frequency for four experimental conditions. The critical cutoff frequencies for reading speed were:

- RSVP and 3rd order Butterworth filter, 1.31 CPL.
- RSVP and Gaussian filter, 1.34 CPL.

⁵ We performed one-way repeated measures ANOVA on critical cutoff (CPL) with task (visual span, reading speed, and single letter recognition) as a within-subject factor. (Please note that the same group of subjects ($n = 7$) participated in all three experiments, visual span, reading speed and single letter recognition for the central viewing condition.)

- Flashcard and 3rd order Butterworth filter, 1.27 CPL.
- Flashcard and Gaussian filter, 1.31 CPL.

We did not find any significant differences in critical cutoffs of reading speeds measured in these four different conditions.

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