Fast and Slow Readers and the Effectiveness of the Spatial Frequency Content of Text: Evidence from Reading Times and Eye Movements

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Fast and Slow Readers and the Effectiveness of the Spatial Frequency Content of Text:

Evidence from Reading Times and Eye Movements

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Abstract

Text contains a range of different spatial frequencies but the effectiveness of spatial frequencies for normal variations in skilled adult reading ability is unknown. Accordingly, young skilled adult readers showing fast or slow reading ability read sentences displayed as normal or filtered to contain only very low, low, medium, high, or very high spatial frequencies. Reading times and eye movement measures of fixations and saccades assessed the effectiveness of these displays for reading. Reading times showed that, for each reading ability, medium, high, and very high spatial frequencies were all more effective than lower spatial frequencies. Indeed, for each reading ability, reading times for normal text were maintained when text contained only medium, high, or very high spatial frequencies. However, reading times for normal text and for each spatial frequency were all substantially shorter for fast readers than for slow readers, and this advantage for fast readers was similar for normal, medium, high, and very high spatial frequencies but much larger for low and very low spatial frequencies. In addition, fast readers made fewer and shorter fixations, fewer and shorter regressions, and longer forward saccades, than slow readers, and these differences were generally similar in size for normal, medium, high, and very high spatial frequencies, but larger when spatial frequencies were lower. These findings suggest that fast and slow adult readers can each use a range of different spatial frequencies for reading but fast readers make more effective use of these spatial frequencies and especially those that are lower.

Reading relies on making saccadic eye movements and ending each movement with a brief fixational pause during which time visual information is acquired from the text (see Rayner, 2009). However, the nature of the visual information acquired during each fixation, and its effectiveness for reading, are not fully known.

Of particular relevance is that visual pathways exist that are selectively sensitive to spatial frequencies associated with different scales of information (e.g., Blakemore & Campbell, 1969; Lovegrove, Bowling, Badcock, & Blackwood, 1980; Robson, 1966). Accordingly, when reading, the visual system acquires a range of different spatial frequencies from text and these spatial frequencies then provide the bases for subsequent linguistic analyses that allow readers to make sense of what they are seeing. For example, lower spatial frequencies allow readers to see a word's coarse overall shape but not its fine detail, whereas higher spatial frequencies allow readers to see a word's fine detail, such as the precise form and location of individual letters, but are less useful for seeing a word's overall shape (e.g., Allen, Smith, Lien, Kaut, & Canfield, 2009; Jordan, 1990, 1995; Kwon & Legge, 2012; Legge, Pelli, Rubin, & Schleske, 1985; Patching & Jordan, 2005a,b). Thus, although spatial frequencies are not apparent to the reader, reading relies fundamentally on these low-level visual properties of text.

However, the effectiveness of different spatial frequencies for reading and how this effectiveness differs for skilled adult readers of different reading abilities have yet to be established. Of particular importance is that while skilled adult reading generally is fast (up to 400-500 words per minute), individual differences in reading speed are a normal component of the skilled adult reading population (e.g., Andrews, 2008, 2012; Ashby, Yang, Evans, & Rayner, 2012; Jackson & McClelland, 1975; Rayner, Slattery, & Bélanger, 2010). One possibility is that fast reading involves better use of predictive processes, such as parafoveal previews and sentence context (e.g., Hawelka, Schuster, Gagl, & Hutzler, 2015; Hersch & Andrews, 2012; Long, Oppy, & Seely, 1994; Murray & Burke, 2003). But many researchers have argued that fast reading is facilitated greatly by "bottom-up" processes which enable fast readers to gain visual access to the correct lexical representations more rapidly. For

example, according to the lexical quality hypothesis of reading skill (e.g., Perfetti, 1992, 2007; see also Andrews, 2008, 2012; Veldre & Andrews, 2014), fast readers have high-quality lexical representations in which orthographic information defining a particular word is stored precisely and this ensures that a word can activate its correct lexical representation directly from the visual input. In this way, high lexical quality is based on the availability of accurate lexical representations which can be accessed efficiently during reading (Perfetti, 2007), and other researchers have suggested that such enhanced lexical access may also allow reading to be more automatic (Ruthruff, Allen, Lien, & Grabbe, 2008). In contrast, the lexical representations of slow readers are underspecified such that the stored orthographic information defining a particular word is imprecise, and rapid bottom-up reading is prevented (e.g., Andrews, 2008, 2012; Perfetti, 1992, 2007). Instead, readers with poor lexical representations risk retrieving imprecise or incomplete lexical information, resulting in the need to re-allocate more attention and working memory capacity to word-level processes (Perfetti, 2007).

However, the nature of the visual input that contributes to fast and slow skilled reading ability is not yet completely clear, and previous discussions have generally addressed the role of letter identities and letter positions in this input (e.g., Andrews, 2008, 2012; Perfetti, 1992, 2007). But as we have seen, text contains more basic information in the form of spatial frequencies, and many researchers argue that access to lexical representations may be achieved using a range of different spatial frequencies, even when only coarse information provided by low spatial frequencies is used (e.g., Allen et al., 2009; Jordan, 1990, 1995; Patching & Jordan, 2005a,b). Indeed, whereas high spatial frequencies are conveyed relatively slowly by parvocellular pathways, low spatial frequencies are conveyed by fast magnocellular pathways and so may provide especially rapid activation of lexical entries (for a review, see Hegde, 2008). Consequently, it could be the case that fast and slow skilled adult readers differ in their abilities to use the spatial frequency content of text and that the coarse visual input of low spatial frequencies provides a particularly special advantage for fast readers.

Although numerous studies have investigated the spatial frequency sensitivities shown by dyslexic and non-dyslexic readers (for a review, see Skottun, 2000), the effectiveness of the spatial

frequency content of text for fast and slow skilled adult reading remains to be revealed. So far, direct information on this issue has been provided by Patching and Jordan (2005a) and their findings suggest that briefly-presented single words, filtered to contain only certain spatial frequencies, are identified equally accurately by fast and slow readers. But identification of brief single words is not textual reading, and a wealth of research shows that eye movement behavior intrinsic to normal reading is sensitive to differences in reading performance (e.g., Ashby, Rayner, & Clifton, 2005; Kuperman, & Van Dyke, 2011; Rayner, 2009; Rayner et al., 2010). Indeed, recent investigations (Jordan, McGowan & Paterson, 2012, 2014; Paterson, McGowan, & Jordan, 2012, 2013a,b) found that when lines of text are filtered so that only certain spatial frequencies remain, readers use a broad range of different spatial frequencies, and different spatial frequencies produce different patterns of eye movement behavior. But these studies assessed the role of spatial frequencies generally in reading, and the effectiveness of spatial frequencies specifically for fast and slow skilled adult readers remains to be addressed.

Accordingly, the present research used reading times and eye-movement measures to investigate the effectiveness of different spatial frequencies for fast and slow skilled adult reading by presenting sentences as normal, or filtered to contain only very low, low, medium, high, or very high spatial frequencies (see Figure 1). Aspects of this work were necessarily exploratory and making too many predictions would be over speculative. But if fast reading relies on detailed analyses of orthographic content (as previous discussions of the lexical quality hypothesis suggest), filtered displays should show an advantage for fast readers that is maximal when spatial frequencies provide this level of detail (in displays showing medium to very high spatial frequencies) and this advantage should be greatly reduced (or even absent) with lower spatial-frequency displays. On the other hand, and in line with the points we have raised, if the effective use of lower spatial frequencies is an influential characteristic of fast reading, an advantage for fast readers over slow readers should also be present for lower spatial frequency displays. Indeed, because lower spatial frequencies are processed faster, these spatial frequencies may be especially important for fast reading and so may show an even

larger advantage for fast readers over slow.

Method

Participants

Thirty participants (aged 18-30 years) from the University of Leicester took part in the study and were screened for reading speed. All participants were native English speakers and had normal or corrected-to-normal vision, as determined by Bailey-Lovie (Bailey & Lovie, 1980), ETDRS (Ferris & Bailey, 1996), and Pelli-Robson (Pelli, Robson, & Wilkins, 1988) assessments (see Jordan, McGowan, & Paterson, 2011). In addition, vocabulary was assessed using the Nelson-Denny vocabulary test (Brown, Fishco, & Hanna, 1993).

Following previous practice (e.g., Jackson & McClelland, 1979; Patching & Jordan, 2005a,b; see also Rayner et al., 2010), fast and slow readers were identified by their effective reading speed, which was calculated for each participant by multiplying reading speed in words per minute (wpm) by the proportion of comprehension questions answered correctly. To do this, 4 passages (mean length=526 words) were presented on a high-definition display. Participants were instructed to read all 4 passages normally and each passage was followed by 6 multiple-choice questions that assessed comprehension. As expected for a population of skilled adult readers, all effective reading speeds were within normal parameters, ranging from 226 to 443 wpm. Fast readers were classified as the upper 50% of this range (15 participants) and slow readers were classified as the lower 50% (15 participants), and so effective reading speeds were 325-443 wpm for fast readers and 226-318 wpm for slow readers. Compared to fast readers, slow readers read test passages more slowly, $t(28)=2.65$, $p<.01$, $r=.44$, and had lower comprehension accuracy, $t(28)=3.55$, $p<.01$, $r=.54$. In addition, compared to fast readers, slow readers scored lower on the Nelson-Denny vocabulary test ($t(28)=3.33$, $p<.01$, $r=.52$). However, fast and slow readers did not differ on any tests of visual abilities (all ts<1.3; see Table 1).

Stimuli and Design

Stimuli for the experiment consisted of 120 sentences (see Paterson et al., 2012). Each

sentence was displayed in 1 of 6 display conditions, shown entirely as normal or filtered to leave one of 5 different, 1-octave wide bands of spatial frequencies with low- and high-pass cut-off frequencies of 1.65-3.3, 2.6-5.2, 5.0-10.0, 8.3-16.6, and 10.3-20.6 cycles per degree (see Figure 1). These 5 bands were termed very low, low, medium, high, and very high. All 120 sentences were sampled in a pseudorandom fashion so that each participant was shown a different selection of 20 sentences in each of the 6 display conditions, without repetition of any sentence for any participant, and all sentences were shown equally often in each condition over the experiment. Sentences were shown to each participant in a randomized order. Additional sentences (2 per condition) were used as practice items at the start of each session.

Apparatus and Procedure

Eye movements were recorded using an Eyelink 2K tower-mounted eye-tracker with chin and forehead rest. Viewing was binocular and each participant's right eye movements were sampled at 1000 Hz using pupil-tracking and corneal reflection. Sentences were displayed on a high-definition 19 inch monitor and a 4-letter word subtended approximately 1° (normal size for reading; Rayner & Pollatsek, 1989). The eye-tracker was calibrated at the beginning of the experiment. On each trial, participants fixated a location on the left of the screen, and a sentence was then presented, with its first letter at the fixation location. Participants were instructed to read normally and for comprehension and answered a two alternative forced-choice comprehension question after each sentence.

<div align="center">

Results

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Participants generally showed high levels of performance on the sentence comprehension questions and no differences in comprehension were observed between reading abilities for any of the 6 display types, $F<1.10$. Moreover, all spatial frequencies (except for very low) produced reading comprehension scores (low 93%; medium 96%; high 95%; very high 92%) that were no different from that obtained with normal displays (95%; all ps>.27) and although, as expected, very low spatial frequencies produced a lower level of comprehension (61%) than normal displays ($p<.01$), this level was still above chance ($p<.01$). Sentence reading times, number of fixations, fixation durations,

number of regressions, progressive saccade lengths, and regressive saccade lengths are reported in

Table 2 and reading times are shown graphically in Figure 2. The data for each measure were

analysed using Analyses of Variance with factors reading ability (fast, slow) and display (normal, very

low, low, medium, high, very high), with errors computed across participants (F_1) and sentences (F_2).

Following each analysis, post hoc comparisons (Bonferroni-corrected t tests) examined effects more

closely.

Reading Times

Analyses of reading times showed main effects of reading ability, $F_1(1,28)=52.06$, $p<.001$,

$\eta_p^2=.65$, $F_2(1,118)=403.72$, $p<.001$, $\eta_p^2=.77$, and display, $F_1(5,140)=64.29$, $p<.001$, $\eta_p^2=.70$,

$F_2(5,590)=483.74$, $p<.001$, $\eta_p^2=.80$, and an interaction, $F_1(5,140)=6.46$, $p<.001$, $\eta_p^2=.19$,

$F_2(5,590)=37.37$, $p<.001$, $\eta_p^2=.24$. For fast and slow readers, pairwise comparisons showed reading

times did not differ from normal for medium, high, or very high displays, but were longer for low and

very low than for all other displays (all ps<.01). However, reading times were shorter for fast readers

than for slow readers for each display (all ps<.01) and while this advantage for fast readers was similar

for normal, medium, high, and very high displays (ps>.05), it was substantially larger for low and very

low displays (ps<.01).

Eye Movement Measures

Eye movement measures complemented the findings for reading times (see Tables 2 & 3). In

particular, main effects of reading ability indicated that fast readers made fixations that were fewer in

number and shorter in duration, and regressions that were fewer in number and shorter in length

(progressive saccades were slightly longer overall for fast readers but not significantly so). Main

effects of display were also found, for all eye movement measures (see Tables 2 & 3), and interacted

with reading ability for fixation numbers, fixation durations, regressions, and progressive saccade

lengths (effects of reading ability on regressive saccade lengths were unchanged across displays).

Compared to slow readers, fast readers made fixations that were fewer and shorter in duration and

regressions that were fewer and shorter in length for all displays (ps<.01), and longer progressive

saccades for very low displays ($ps<.01$). For fixation numbers, the extent of the difference between fast and slow readers was similar for normal, medium, high, and very high displays ($ps>.05$) but larger for low and very low ($ps<.01$); for fixation durations, regressions, and progressive saccade lengths, the fast-slow difference was similar for normal, low, medium, high and very high displays ($ps>.05$) but larger for very low ($ps<.01$); and for regressive saccade lengths, the fast-slow difference remained unchanged across displays ($ps>.05$).

Discussion

These findings show that both fast and slow skilled adult readers can use a range of spatial frequencies for textual reading. Indeed, for each reading ability, reading times for normal text were maintained even when text contained only medium, high, and very high spatial frequencies, and reading occurred even for low and very low spatial frequencies, albeit more slowly. However, reading times were substantially shorter for fast readers than for slow readers for all types of display, and although the extent of this advantage for fast readers was similar for normal, medium, high, and very high spatial frequencies, it was considerably larger for low and very low spatial frequencies. Differences between fast and slow readers were also present in the eye movement record, where fast readers made fewer and shorter fixations, fewer and shorter regressions, and longer progressive saccades than slow readers, and fast-slow differences were more apparent when text contained lower spatial frequencies. The indication, therefore, is that fast readers used spatial frequencies more effectively for word identification and eye guidance, and this advantage was greatest for lower spatial frequencies.

The greater effectiveness of medium and higher spatial frequencies for both reading abilities, and the normal levels of performance produced by these frequencies, suggest that fast and slow readers both benefit from relatively detailed analyses of text, allowing perception of the precise form and location of individual letters. This is consistent with views concerning the role of individual letter information generally in reading (e.g., Davis, 2010; Pelli, Farrell, & Moore, 2003) and with the lexical quality hypothesis which proposes that fast reading benefits from high-quality lexical representations

in which orthographic information defining a particular word is stored precisely (e.g., Andrews, 2008, 2012; Perfetti, 1992, 2007).

But the greatest difference between fast and slow readers was the effectiveness of lower spatial frequencies, and the implication from these findings is that although lower spatial frequencies alone are generally less effective than other spatial frequencies for reading, their influence represents an unusually important component of the distinction between fast and slow readers. This resonates with the view that lower spatial frequencies reach cortical areas before higher spatial frequencies (e.g., Allen et al., 2009; Jordan et al., 2012, 2014; Patching & Jordan 2005a,b), and so, compared to slow readers, fast readers may be especially able to use lower spatial frequencies to help gain lexical access more rapidly. Indeed, this ability for fast readers could provide an effective bottom-up basis for influences of predictability that many argue are also part of fast reading (e.g., Hawelka et al., 2015; Hersch & Andrews, 2012; Long et al., 1994; Murray & Burke, 2003). In this sense, if the coarse information provided by lower spatial frequencies in normal text is sometimes insufficient alone to access the correct lexical representation (as the reading performance and comprehension scores observed for lower spatial frequencies suggests), fast readers may be adept at combining the rapid processing of a word's lower spatial frequencies with the context in which the word is encountered to provide top-down predictions of the word's identity, and (if required) integrate this combined information with detail provided by parvocellular pathways. Indeed, and in contrast to higher spatial frequencies, lower spatial frequencies can be encoded from a wide range of locations along a line of text during each fixational pause (in foveal, parafoveal, and peripheral vision; e.g., Jordan et al., 2012; Paterson et al., 2013a,b; see also Jordan, McGowan & Paterson, 2013, Jordan, McGowan, Kurtev, & Paterson, 2016), and so the more effective use of lower spatial frequencies by fast readers may indicate a pragmatic response to the nature of visual sensory input and the complex demands of the process of reading.

In sum, the findings of this study provide fresh insight into the nature of fast and slow skilled adult reading using a technique in which the effectiveness of different spatial frequency bands in text

were determined individually to avoid contamination from other spatial frequencies. Further research can now take place to show how the influences of these spatial frequencies integrate when reading normal text, where different bands of spatial frequencies are naturally present simultaneously and so may exert influences on reading ability either in parallel or in close succession during reading. In addition, the procedures adopted in the present study can also be used to develop fresh insight into the reading abilities of other groups, like dyslexics, where the role of different spatial frequencies also remains to be fully resolved. Indeed, there seems little doubt that continued investigations of the relationship between spatial frequencies and reading will provide further, crucial information about the underlying nature of reading abilities, and this serves to emphasize the importance of investigating textual reading from a visual perspective as well as from the perspective of higher-order cognitive functions.

References

Allen, P. A., Smith, A. F., Lien, M. C., Kaut, K. P., & Canfield, A. (2009). A multi-stream model of

visual word recognition. *Attention, Perception, & Psychophysics, 71*, 281-296.

doi:10.3758/APP.71.2.281

Andrews, S. (2008). Lexical expertise and reading skill. *Psychology of Learning and Motivation, 49*,

249-281.

Andrews, S. (2012). Individual differences in skilled visual word recognition and reading: The role of

lexical quality. In J. Adelman (Ed.), *Visual word recognition* (pp. 151-172). Hove:

Psychology Press.

Ashby, J., Rayner, K., & Clifton, C. (2005). Eye movements of highly skilled and average readers:

Differential effects of frequency and predictability. *Quarterly Journal of Experimental*

Psychology, 58, 1065-1086. doi: 10.1080/02724980443000476

Ashby, J., Yang, J., Evans, K., & Rayner, K. (2012). Eye movements and the perceptual span in silent

and oral reading. *Attention, Perception, & Psychophysics, 74*, 634-640.

Bailey, I. L., & Lovie, J. E. (1980). The design and use of a new near-vision chart. *American Journal*

of Optometry and Physiological Optics, 57, 378-387. doi:10.1097/00006324-198006000-

00011

Blakemore, C., & Campbell, F. W. (1969). Adaptation to spatial stimuli. *Journal of Physiology, 200*,

11-13.

Brown, J. I., Fishco, V. V., & Hanna, G. (1993). *The Nelson-Denny reading test*. Itasca, IL: The

Riverside Publishing Company.

Davis, C. J. (2010). The spatial coding model of visual word identification. *Psychological Review,*

117, 713-758.

Ferris, F. L., & Bailey, I. L. (1996). Standardizing the measurement of visual acuity for clinical

research studies. *Ophthalmology, 103*, 181-182. doi:10.1016/S0161-6420(96)30742-2

Hawelka, S., Schuster, S., Gagl, B., & Hutzler, F. (2015). On forward inferences of fast and slow

readers. An eye movement study. *Scientific Reports 5,* 8432

Hegde J. (2008). Time course of visual perception: coarse-to-fine processing and beyond. *Progress in Neurobiology, 84*, 405-439.

Hersch, J., & Andrews, S. (2012). Lexical quality and reading skill: Bottom-up and top-down contributions to sentence processing. *Scientific Studies of Reading, 16*, 240-262.

Jackson, M. D., & McClelland, J. L. (1979). Processing determinants of reading speed. *Journal of Experimental Psychology: General, 108*, 151-181.

Jordan, T. R. (1990). Presenting words without interior letters: Superiority over single letters and influence of postmask boundaries. *Journal of Experimental Psychology: Human Perception and Performance, 16*, 893-909. doi:10.1037/0096-1523.16.4.893

Jordan, T. R. (1995). Perceiving exterior letters of words: Differential influences of letter-fragment and nonletter fragment masks. *Journal of Experimental Psychology: Human Perception and Performance, 21*, 512-530. doi:10.1037/0096-1523.21.3.512

Jordan, T. R., McGowan, V. A., Kurtev, S., & Paterson, K. B (2016). A further look at postview effects in reading: An eye-movements study of influences from the left of fixation. *Journal of Experimental Psychology: Learning, Memory, and Cognition 42*, 296-307

Jordan, T. R., McGowan, V. A., & Paterson, K. B. (2011). Out of sight, out of mind: The rarity of assessing and reporting participants' visual abilities when studying perception of linguistic stimuli. *Perception, 40*, 873-876. doi:10.1068/pp.6940

Jordan, T. R., McGowan, V. A., & Paterson, K. B. (2012). Reading with a filtered fovea: The influence of visual quality at the point of fixation during reading. *Psychonomic Bulletin & Review, 19*, 1078-1084. doi: 10.3758/s13423-012-0307-x

Jordan, T.R., McGowan, V.A., & Paterson, K.B. (2013). What's left? An eye-movement study of the influence of interword spaces to the left of fixation during reading. *Psychonomic Bulletin & Review, 20*, 551-557.

Jordan, T. R., McGowan, V. A., & Paterson, K. B. (2014). Reading with filtered fixations: Adult-age

differences in the effectiveness of low-level properties of text within central vision. *Psychology and Aging, 29*, 229-235.

Kuperman, V., & Van Dyke, J. A. (2011). Effects of individual differences in verbal skills on eye-movement patterns during sentence reading. *Journal of Memory and Language, 65*, 42-73. doi: 10.1016/j.jml.2011.03.002

Kwon, M., & Legge, G. E. (2012). Spatial-frequency requirements for reading revisited. *Vision Research, 62*, 139-147. doi:10.1016/j.visres .2012.03.025

Legge, G. E., Pelli, D. G., Rubin, G. S., & Schleske, M. M. (1985). Psychophysics of reading: I. Normal vision. *Vision Research, 25,* 239-252. doi:10.1016/0042-6989(85)90117-8

Long, D. L., Oppy, B. J., & Seely, M. R. (1994). Individual differences in the time course of inferential processing. *Journal of Experimental Psychology: Learning, Memory, and Cognition. 20*, 1456-1470.

Lovegrove, W. J., Bowling, A., Badcock, D., & Blackwood, M. (1980). Specific reading disability: Differences in contrast sensitivity as a function of spatial frequency. *Science, 210*, 439-440. doi:10.1126/science.7433985

Murray, J. D., & Burke, K. A. (2003). Activation and encoding of predictive inferences: The role of reading skill. *Discourse processes. 35*, 81-102.

Patching, G. R., & Jordan, T. R. (2005a). Assessing the role of different spatial frequencies in word perception by good and poor readers. *Memory & Cognition, 33*, 961-971. doi:10.3758/BF03193205

Patching, G. R., & Jordan, T. R. (2005b). Spatial frequency sensitivity differences between adults of good and poor reading ability. *Investigative Ophthalmology & Visual Science, 46*, 2219-2224. doi:10.1167/iovs.03-1247

Paterson, K. B., McGowan, V. A., & Jordan, T. R. (2012). Eye movements reveal effects of visual content on eye guidance and lexical access during reading. *PLoS ONE 7(8): e41766.doi:10.1371/journal.pone.0041766*

Paterson, K. B., McGowan, V. A., & Jordan, T. R. (2013a). Effects of adult aging on reading filtered

   text: Evidence from eye movements. PeerJ, 1, e63. doi:10.7717/peerj.63

Paterson, K. B., McGowan, V. A., & Jordan, T. R. (2013b). Filtered text reveals adult age differences

   in reading: Evidence from eye movements. *Psychology and Aging, 28*, 352-364.

   doi:10.1037/a0030350

Pelli, D. G., Farell, B., & Moore, D. C. (2003). The remarkable inefficiency of word recognition.

   Nature, 423, 752-756.

Pelli, D. G., Robson, J. G., & Wilkins, A. J. (1988). The design of a new letter chart for measuring

   contrast sensitivity. *Clinical Vision Science, 2*, 187-199.

Perfetti, C. A. (1992). The representation problem in reading acquisition. In P. B. Gough, L. C. Ehri,

   & R. Treiman (Eds.), *Reading acquisition* (pp. 145-174). Hillsdale, NJ: Lawrence Erlbaum

   Associates.

Perfetti, C. A. (2007). Reading ability: Lexical quality to comprehension. *Scientific Studies of*

   Reading. 11, 357-383.

Rayner, K. (2009). Eye movements and attention in reading, scene perception, and visual search. *The*

   Quarterly Journal of Experimental Psychology, 62, 1457-1506.

Rayner, K., & Pollatsek, A. (1989). *The Psychology of Reading*. Englewood Cliffs: Prentice-Hall.

Rayner, K., Slattery, T. J., & Bélanger, N. N. (2010). Eye movements, the perceptual span, and

   reading speed. *Psychonomic Bulletin & Review*, *17*, 834-839.

Robson, J. G. (1966). Spatial and temporal contrast sensitivity functions of the visual system.

   Journal of the Optical Society of America, 56, 1141-1142.

Ruthruff, E., Allen, P. A., Lien, M.-C., & Grabbe, J. (2008). Visual word recognition without central

   attention: Evidence for greater automaticity with greater reading ability. *Psychonomic Bulletin*

   & Review, 15, 337-343.

Skottun, B. C. (2000). The magnocellular deficit theory of dyslexia: the evidence from contrast

   sensitivity. *Vision Research, 40*, 111-127.

Veldre, A., & Andrews, S. (2014). Lexical quality and eye movements: Individual differences in the

    perceptual span of skilled adult readers. *The Quarterly Journal of Experimental Psychology,*

    67, 703-727.

Figure Legends

Figure 1. Examples of the types of display used in the experiment. The figure shows a sentence displayed as normal and filtered to contain only very low, low, medium, high, or very high spatial frequencies. The visual appearance of the filtered displays shown in the figure is approximate due to variations in display resolution and print medium.

Figure 2. Mean Reading Times (including standard error bars) for fast and slow readers.

Figure 1

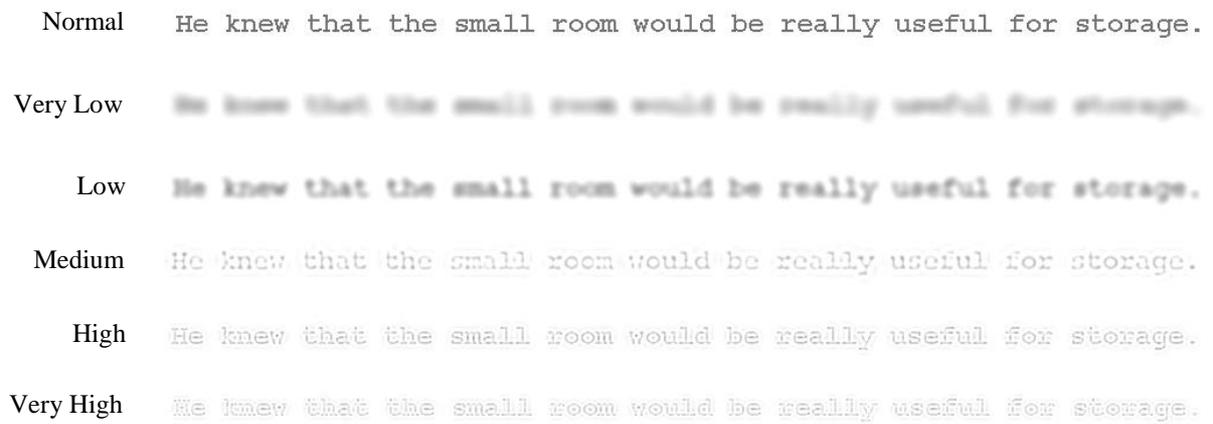|	
Normal	He knew that the small room would be really useful for storage.
Very Low	He knew that the small room would be really useful for storage.
Low	He knew that the small room would be really useful for storage.
Medium	He knew that the small room would be really useful for storage.
High	He knew that the small room would be really useful for storage.
Very High	He knew that the small room would be really useful for storage.

Figure 2

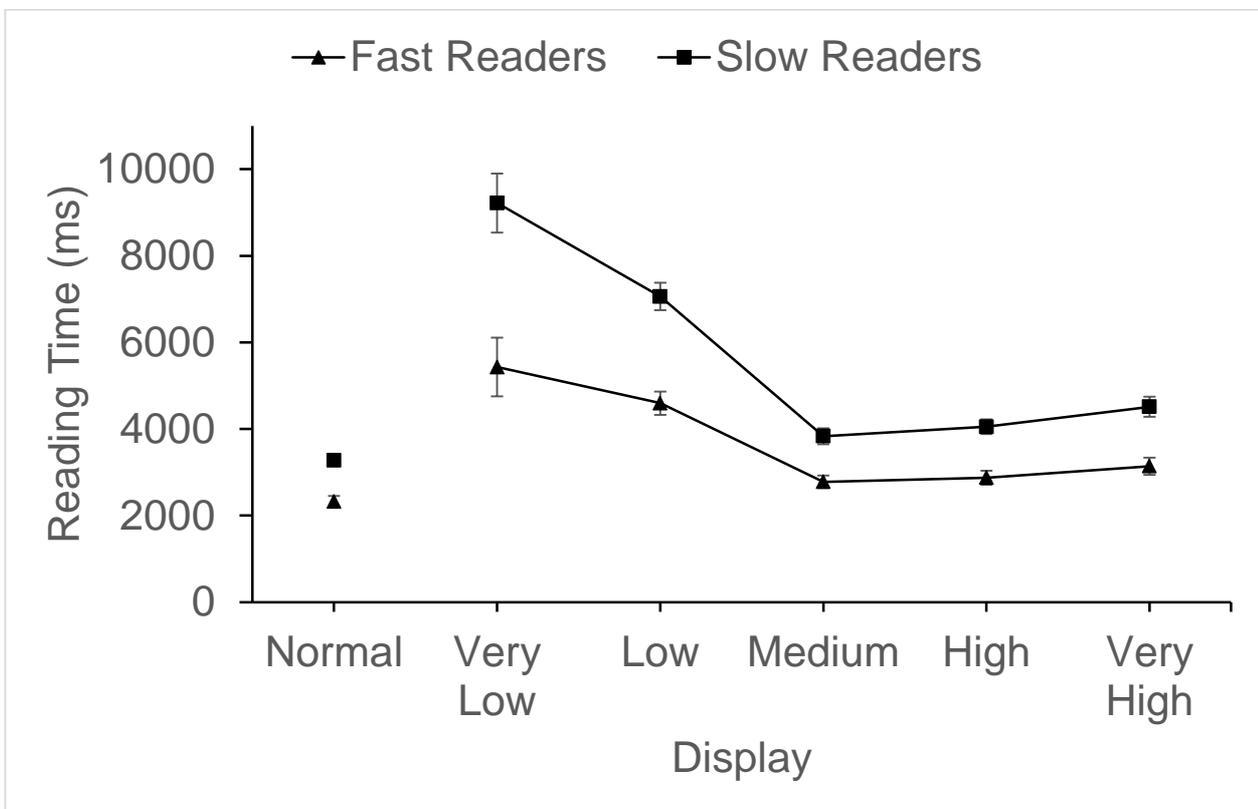Table 1. Visual and Vocabulary Performance of Fast and Slow Readers

Reading Ability	High Contrast Acuity (Near)	High Contrast Acuity (Distant)	Low Contrast Acuity (Near)	Low Contrast Acuity (Distant)	Contrast Sensitivity	Vocabulary
Fast	20/20.6	20/21.2	20/26.6	20/32.8	1.95	92%
Slow	20/20.4	20/23.4	20/27.9	20/33.2	1.95	80%

Table 2. Mean Reading Times and Mean Eye Movement Measures for Fast and Slow Readers in Each Display Condition

		Display Condition					
	Reading Ability	Normal	Very Low	Low	Medium	High	Very High
Reading Times (ms)	Fast	2325 (150)	5430 (676)	4595 (271)	2780 (144)	2873 (163)	3138 (201)
	Slow	3272 (128)	9219 (682)	7060 (319)	3832 (183)	4051 (169)	4512 (230)
Number of Fixations	Fast	10.3 (2.7)	15.2 (3.9)	15.7 (4.1)	11.7 (3.0)	11.9 (3.1)	12.4 (3.2)
	Slow	13.4 (3.5)	22.7 (5.9)	21.7 (5.6)	14.7 (3.8)	15.4 (4.0)	16.0 (4.1)
Fixation Durations (ms)	Fast	217 (4)	336 (12)	280 (6)	233 (4)	238 (6)	250 (7)
	Slow	241 (8)	383 (12)	310 (10)	256 (7)	259 (8)	276 (9)
Number of Regressions	Fast	1.9 (.3)	3.6 (.6)	3.7 (.4)	2.2 (.3)	2.1 (.3)	2.1 (.3)
	Slow	3.0 (.3)	7.1 (1.1)	5.7 (.3)	3.3 (.3)	3.2 (.3)	3.4 (.3)
Progressive Saccade Lengths (in characters)	Fast	10.4 (.4)	9.2 (1.1)	8.8 (.4)	9.6 (.4)	9.2 (.4)	8.8 (.4)
	Slow	10.0 (.4)	8.1 (.4)	8.4 (.2)	8.4 (.2)	9.2 (.3)	8.4 (.3)
Regressive Saccade Lengths (in characters)	Fast	17.2 (1.1)	10.8 (.4)	11.6 (.4)	15.6 (.9)	16.4 (.9)	14.7 (1.0)
	Slow	20.4 (1.7)	14.0 (1.0)	12.8 (.9)	17.6 (1.0)	18.8 (1.2)	23.0 (1.5)

Table 3. F_1 and F_2 Statistics for Eye-Movement Measures of Reading

		F_1			F_2		
	Source of variance	df	Value	η_p^2	df	Value	η_p^2
Number of Fixations	Reading Ability	1,28	31.11***	.53	1,118	261.85***	.69
	Display Type	5,140	27.84***	.50	5,590	174.51***	.60
	Reading Ability x Display Type	5,140	2.63*	.09	5,590	11.61***	.09
Fixation Durations	Reading Ability	1,28	8.22**	.23	1,118	332.24***	.74
	Display Type	5,140	218.80***	.89	5,590	458.11***	.80
	Reading Ability x Display Type	5,140	2.26*	.08	5,590	4.62***	.04
Number of Regressions	Reading Ability	1,28	14.00**	.33	1,118	203.04***	.63
	Display Type	5,140	21.93***	.44	5,590	86.71***	.42
	Reading Ability x Display Type	5,140	3.66**	.12	5,590	14.47***	.11
Progressive Saccade Lengths	Reading Ability	1,28	1.63	.06	1,118	32.29***	.22
	Display Type	5,140	7.74***	.21	5,590	68.51***	.37
	Reading Ability x Display Type	5,140	3.11**	.10	5,590	4.96***	.04
Regressive Saccade Lengths	Reading Ability	1,28	4.18*	.15	1,118	15.62***	.12
	Display Type	5,140	32.38***	.54	5,590	60.24***	.34
	Reading Ability x Display Type	5,140	.83	.03	5,590	1.15	.01

* $p<.05$, ** $p<.01$, *** $p<.001$