

Speed discrimination predicts word but not pseudo-word reading rate in adults and children



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ARTICLE INFO

Article history:

Accepted 2 September 2014

Keywords:

Reading
Speed discrimination
Contrast sensitivity
Dorsal stream
Magnocellular pathway

ABSTRACT

Visual processing in the magnocellular pathway is a reputed influence on word recognition and reading performance. However, the mechanisms behind this relationship are still unclear. To explore this concept, we measured reading rate, speed-discrimination, and contrast detection thresholds in adults and children with a wide range of reading abilities. We found that speed discrimination thresholds are higher in children than in adults and are correlated with age. Speed discrimination thresholds are also correlated with reading rates but only for real words, not pseudo-words. Conversely, we found no correlations between contrast detection thresholds and the reading rates. We also found no correlations between speed discrimination or contrast detection and WASI subtest scores. These findings indicate that familiarity is a factor in magnocellular operations that may influence reading rate. We suggest this effect supports the idea that the magnocellular pathway contributes to word reading through an analysis of letter position.

Published by Elsevier Inc.

1. Introduction

Reading involves the coordination of brain areas that process visual and phonological information (Schlaggar & McCandliss, 2007). Reading begins with the visual recognition of orthography, the patterned symbols that constitute letters and words. This information is then translated into phonological representations by cortical areas specialized in language. Here we focus on the visual component of this process and submit evidence that word familiarity is a factor in magnocellular operations that may support reading rate.

Historically, cognitive theorists have studied visual word recognition as the first step of the reading process. Selfridge (1959) developed one of the earliest models of pattern recognition for letters. McClelland and Rumelhart later explored visual word recognition through their interactive activation model (McClelland & Rumelhart, 1981; Rumelhart & McClelland, 1982). Several other reading models followed, attempting to describe the cognitive interplay between word recognition, phonology, and semantics

(Coltheart, Curtis, Atkins, & Haller, 1993; Coltheart, Rastle, Perry, Langdon, & Ziegler, 2001; Dehaene, Cohen, Sigman, & Vinckier, 2005; Grainger, Grainer, Farioli, Van Assche, & van Heuven, 2006; Grainger & Jacobs, 1996; Harm & Seidenberg, 2004; Hinton & Shallice, 1991; Morrison, 1984; Plaut, McClelland, Seidenberg, & Patterson, 1996; Seidenberg & McClelland, 1989; Whitney, 2001).

All of these models set visual information as the primary input and seek to explain the variety of behavioral data in word recognition. One consistent finding is that frequency and familiarity matter. Experience with specific words improves performance for those items on perceptual identification (Broadbent, 1967), lexical decision (Forster & Chambers, 1973), and naming tasks (Balota & Chumbley, 1984). Research also shows skilled readers have faster word naming times than less skilled readers (Mason, 1978). In reading, like any other cognitive process, more experience with an operation enhances performance of that operation. It is likely that fast recognition of words contributes significantly to efficient reading.

A growing literature suggests individual differences in word recognition and reading performance may stem, in part, from the functioning of the brain's visual system (for a review see Boden & Giaschi, 2007). The primate visual system consists of at least two parallel processing streams, the magnocellular (M) and parvo-

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cellular (P) pathways (Shapley, 1990). The P pathway processes high-spatial, low-temporal chromatic information (Merigan, Katz, & Maunsell, 1991). The M pathway, in contrast, is more sensitive to luminance, low spatial-frequencies, and high temporal-frequencies (Merigan, Byrne, & Maunsell, 1991).

Approximately 10% of retinal ganglion cells are classified as magnocellular (Shapley & Perry, 1986). Their receptive fields cover relatively large portions of the visual field and they project strongly myelinated (fast conducting) axons downstream to the lateral geniculate nucleus (LGN). Lesion experiments in the LGN have shown M pathway deficits are identifiable through tests of contrast sensitivity, flicker resolution, and motion detection/discrimination (Merigan, Byrne, et al., 1991; Merigan, Katz, et al., 1991; Merigan & Maunsell, 1990; Schiller, Logothetis, & Charles, 1990). Psychophysical tasks incorporating these elements have become standard behavioral measures of magnocellular processing.

Reading achievement is correlated with performance on two agreed measures of the M pathway: coherent motion detection (Cornelissen, Bradley, Fowler, & Stein, 1994; Cornelissen, Hansen, Hutton, Evangelinou, & Stein, 1998b) and velocity discrimination (Demb, Boynton, & Heeger, 1997, 1998). This relationship suggests the M pathway may be a factor in reading ability. If this is the case, the mechanism remains unknown. One theory is the magnocellular pathway could impact reading by processing contrast sensitivity.

Deficits in contrast sensitivity could impair the visual analysis of features that compose letters and words, slowing word recognition and reading rate. Research indicates that individuals with impaired contrast sensitivity have slower peak reading rates (Akutsu, Legge, Ross, & Schuebel, 1991), slower overall reading rates (Legge, Pelli, Rubin, & Schleske, 1984), and longer fixations during reading (De Luca, Spinelli, & Zoccolotti, 1996). Some researchers have proposed that dyslexics have reduced contrast sensitivity and this may be the cause of their impairment (Borsting et al., 1996; Edwards et al., 2004; Evans, Drasdo, & Richards, 1994; Felmingham & Jakobson, 1995; Lovegrove et al., 1982; Martin & Lovegrove, 1984, 1987; Mason, Cornelissen, Fowler, & Stein, 1993), though others have disputed these claims (Ben-Yehudah, Sackett, Malchi-Ginzberg, & Ahissar, 2001; Cornelissen, Richardson, Mason, Fowler, & Stein, 1995; Gross-Glenn et al., 1995; Hayduk, Bruck, & Cavanagh, 1996; Williams, Stuart, Castles, & McAnally, 2003).

Another way the M pathway could influence reading is by directing attention to the positional relationships among letters, a process called position encoding. Models of orthographic processing describe a spatial accounting of the features that compose words (Dehaene et al., 2005; Grainger et al., 2006; Whitney, 2001). In models such as SERIOL (Whitney, 2001), a representation is built from the interaction of neural ensembles that code edges, letters, bigrams (letter pairs), then finally the whole word. The allocation of visual attention to familiar stimuli is likely a key factor in this process. Word representations are strengthened by repeated attention to specific letters and letter combinations (Whitney, 2001; Whitney & Cornelissen, 2005). In this way, stimulus familiarity may aid position encoding, speed word recognition, and ultimately enhance reading rate.

Experimental research demonstrates the effects of familiarity and position encoding on reading tasks. Mason (1978) reported familiarity effects in an analysis of word naming times. The general finding was that word naming is faster for skilled compared to less skilled readers. Additionally, naming time was increased in all participants by factors that reduce the familiarity of adjacent letters, such as using mixed-case words (i.e., MiXeD CaSe) and pronounceable pseudo-words (i.e., worthy vs. werply). Mason (1980) also showed the ability to code letter spatial position differentiates readers. She assessed letter and location identification in adults grouped as highly skilled or less skilled readers. Performance

between the groups was similar when identifying single letters in brief displays. However, skilled readers were significantly more accurate at identifying the serial position of a letter. This effect occurred in both word and non-word displays. Such findings suggest the visual perception of letter position and letter spatial relationships are important factors in word recognition and efficient reading.

Position encoding also seems to be tied to motion perception. Cornelissen and Hansen (1998) and Cornelissen et al. (1998a) measured coherent motion detection and accuracy on a single-word reading task in groups of school children. The reading task assessed “letter errors”, instances where participants confused letter positions in sounding out words. They found a positive correlation between motion detection thresholds and the number of letter errors. In a follow up with adults, Cornelissen et al. (1998a) classified participants as having either good or poor motion detection then tested them on a number of reading-based measures. They found the group with better motion detection was also more accurate on tasks dependent on position encoding, such as lexical decision for words or anagrams and primed reaction time for letters and non-alphabetic foils.

If the M pathway supports efficient reading through an analysis of letter position then word familiarity may be a factor. The letter combinations of familiar words may prompt fast recognition from a visual lexicon, whereas unfamiliar words require a longer, letter-by-letter analysis (Coltheart et al., 1993, 2001). If this is the case, the reading rates of familiar words may be more correlated with M pathway measures than the reading rates of unfamiliar words. In contrast, if magnocellular processing supports reading rate through other mechanisms, such as contrast sensitivity, word familiarity would not affect these correlations.

In the current study we sought to investigate the effect of word familiarity on correlations between reading rate, magnocellular thresholds, and general intelligence measures. We correlated psychophysical thresholds (speed discrimination and contrast detection) with reading rates in adults and children with a wide range of reading abilities. To manipulate familiarity, we assessed reading rates for real and pseudo-words using the Test of Word Reading Efficiency (TOWRE). Pseudo-words are pronounceable non-words and are consequently less familiar to participants than real words. To evaluate the M pathway, speed discrimination and contrast detection tasks were administered in a mesopic environment using parameters described in Demb, Boynton, Best, and Heeger (1998) and Demb, Boynton, and Heeger (1998). The Wechsler Abbreviated Scale of Intelligence (WASI) measured aspects of general intelligence such as reasoning and vocabulary skills.

Our approach to the data is as follows: 1. If familiarity is a factor in magnocellular processes that may influence reading rate, we expect a dissociation between correlations involving speed discrimination and the different reading rates (real and pseudo-word). There should be significant correlations between speed discrimination and real word reading rates. However, because pseudo-words are less familiar than real words, we anticipate diminished or no correlations for pseudo-word reading rates. 2. In contrast, if familiarity is not a factor in these magnocellular processes, we expect no differences between correlations of speed discrimination the above reading rates. 3. If contrast sensitivity is a factor in magnocellular processes, we expect significant correlations between contrast detection thresholds and the reading rates. 4. If contrast sensitivity is not a factor, correlations with contrast detection should be non-significant. This analysis could support speed discrimination or contrast detection as predictive of reading rates, real or pseudo-words, or combinations thereof.

While others have studied the relationship between motion perception and reading ability, our examination focused specifically on relationships between word familiarity, the M pathway,

and reading rates. We present data on these relationships across a range of ages and reading abilities: children and adults, skilled and poor readers – i.e., dyslexics. We provide additional insight by using speed discrimination as an index for reading performance. The overwhelming majority of studies examining motion sensitivity and reading have used motion coherence as a measure (for a review see Benassi, Simonelli, Giovagnoli, & Bolzani, 2010). Only a handful of studies have used speed discrimination to explore associations between vision and reading ability (Demb, Boynton, Best, & Heeger, 1998; Demb, Boynton, & Heeger, 1998; Ramus et al., 2003; Wilmer, Richardson, Chen, & Stein, 2004). This is despite evidence it may be a more accurate proxy for reading fluency (Wilmer et al., 2004). Here we use speed discrimination as a measure of motion sensitivity because it may be more relevant to reading rate and better at differentiating skilled readers.

We report three findings: 1. Reading rates correlate with speed discrimination but not contrast detection thresholds. 2. Speed discrimination thresholds correlate with the reading rate for real words but not pseudo-words. 3. Finally, neither contrast detection nor speed discrimination correlate with cognitive measures independent of vision such as analytical reasoning and vocabulary. We argue that the correlations between real word reading rates and speed discrimination support the idea that efficient reading involves magnocellular functions that analyze letter position.

2. Material and methods

2.1. Participants

Twenty-eight (28) participants were recruited from the Stanford University student body and the Palo Alto community (14 adults, age 18–53; 14 children, age 6–16). Four of the adults and seven of the children were diagnosed with developmental dyslexia. Three of the children had recognized reading difficulties, but had never been diagnosed with dyslexia. All participants were pre-screened for neurological conditions and language history. English was the first language of those selected to participate. The participants were consented according to Stanford University IRB guidelines.

2.2. Psychological testing

2.2.1. TOWRE

Participants completed forms A and B of the Test of Word Reading Efficiency or TOWRE, a timed measure of verbal fluency and accuracy (Torgesen et al., 1999). Participants read two lists for each form: Sight Word Efficiency (SWE) and Phonemic Decoding Efficiency (PDE). The SWE list consists of 104 English words. The PDE list consists of 63 pronounceable pseudo-words with no recognized English meaning. Participants were instructed to read the lists as fast as possible while maintaining pronunciation. For each list, the experimenter recorded the number of words participants were able to read in 45 s, not counting miss-readings, mispronunciations, and skipped items.

2.2.2. WASI

Participants completed the Vocabulary and Matrix Reasoning subtests of the Wechsler Abbreviated Scale of Intelligence (Wechsler, 1999). For the Vocabulary subtest, participants were presented with cards printed with words appropriate to their age level. Their task was to verbally define each word in as much detail as possible. Participants had approximately 30 s to respond to each item (42 total) or it was counted wrong. Different start and stop points were observed according to the age group. After testing

the experimenter scored the word definitions on accuracy and detail using a 0–2 point scale.

In the Matrix Reasoning subtest, participants were presented with cards depicting a 2×2 matrix. Three of the cells in the matrix contained abstract forms. Participants were instructed to identify the most appropriate form to complete the matrix from an array of five choices. Participants had approximately 30 s to finish each item (35 total) or it was scored as incorrect.

2.3. Psychophysics

All psychophysics testing took place in a mesopic environment where the primary light source was a computer monitor. Participants were seated 57 cm from a 21-in. CRT monitor. Neutral density filters affixed to the screen reduced the mean screen luminance to 4 cd/m^2 . All stimuli appeared over a gray background. A chin rest ensured the correct distance and minimized head movement. Participants made responses on a Qwerty keyboard with their dominant hand. Two-alternative, interval choice (2IFC) procedures measured speed discrimination and contrast detection (Fig. 1). The tasks were programmed and run on a Mac OS X laptop using MGL (<http://gru.brain.riken.jp/mgl>), a freeware psychophysics package based in MATLAB.

An experimenter was present throughout testing to start the programs and keep participants on task. Extra care was taken to make sure that the behavioral data collected could be compared across age range. Participants completed about 20–60 practice trials before data collection. An experimenter sat on the side of the participants and verbally motivated each individual to focus on

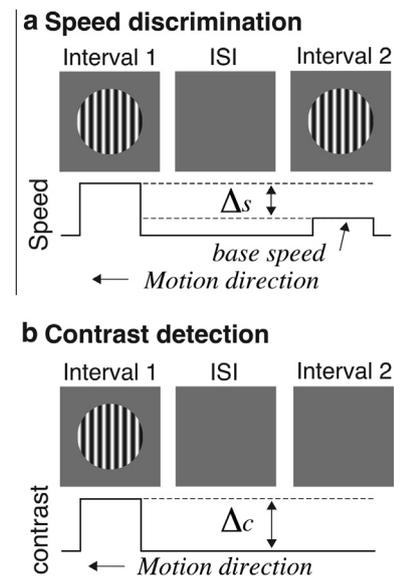


Fig. 1. Psychophysics protocol. a. Speed discrimination task. *Top:* Gratings (5° in diameter, 0.5 c/° spatial frequency) were presented at the center of the screen in two 375-ms long intervals separated by an inter-stimulus interval of 250 ms. Gratings in both intervals had the same contrast (either 16% or 24%). *Bottom:* On every trial one of the stimuli drifted from right to left at $38^\circ/\text{s}$ (base speed), the other had a higher drift speed (base speed + Δs). Participants indicated the temporal interval containing the faster grating. The speed difference between the two gratings (Δs) was adjusted on each trial by an adaptive staircase procedure to measure the 75% speed discrimination. b. Contrast detection task. *Top:* Gratings (5° in diameter, 0.5 c/° spatial frequency) were presented at the center of the screen in two 375-ms long intervals separated by an inter-stimulus interval of 250 ms. Only one randomly-chosen interval contained the target grating (first in the figure). *Bottom:* Gratings drifted right to left at $38^\circ/\text{s}$. Participants indicated the temporal interval containing the target grating with a key press. The contrast of the target grating (Δc) was changed on each trial by an adaptive staircase procedure to measure the 75% contrast detection threshold (QUEST; Watson & Pelli, 1983).

the upcoming stimulus before each trial. Sessions with more than five consecutive missed responses were aborted and the data discarded.

2.3.1. Speed discrimination

Participants fixated on a circle at the center of the screen. Each trial consisted of two temporal intervals in which a Gaussian windowed grating appeared over the fixation circle. All gratings were 5° in diameter and had a spatial frequency of 0.5 c/°. The contrast of the gratings was either 16% or 24%, randomized trial-to-trial. The stimulus duration was 375 ms with an inter-stimulus interval of 250 ms. Gratings drifted right to left at a base speed of 38 °/s. On every trial, presentations were randomized so one grating was animated at the base speed, the other at a faster, target speed. Participants indicated the temporal interval with the faster grating by pressing corresponding keys during the inter-trial interval. Key presses had to be within 1.6 s or the response was dropped. Trial-to-trial variation in target speed was controlled by the QUEST adaptive staircase (Watson & Pelli, 1983).

2.3.2. Contrast detection

Participants fixated on the center of the screen and viewed Gaussian windowed gratings under the same parameters as speed discrimination: two temporal intervals of 375 ms and an inter-trial interval of 250 ms. The speed of the gratings (38 °/s) was constant for all stimuli. The order of the temporal intervals was randomized. One interval contained a target grating of varying contrast; the other did not. Participants indicated the temporal interval with the grating by a key press during the inter-trial interval. The QUEST adaptive staircase varied target contrast according to participant responses.

2.4. Data analysis

2.4.1. Threshold determination

We calculated psychophysical thresholds in three ways. 1. *QUEST median value*: Contrast and speed discrimination thresholds (Weber fraction) were first computed as the median of the QUEST run. The standard QUEST analysis assumes a fixed slope (3.5; Watson & Pelli, 1983) for the psychometric function and computes the threshold corresponding to a 76% correct response rate. To ensure thresholds estimates were not biased by these assumptions, we confirmed our findings in two additional ways. 2. *Fitted slope*: We re-ran the QUEST analysis allowing both threshold and slope to vary as free parameters, fitting the psychometric function in each individual observer. 3. *Median intensity*: Finally, we calculated the thresholds as the median stimulus intensity presented over the total number of trials across all runs for each observer. This analysis does not assume any model for the final estimation of the psychometric function.

2.4.2. Correlation coefficients

To address whether psychophysical performance is related to reading performance, we calculated correlation coefficients (Pearson's r) between reading rates and mesopic thresholds (velocity discrimination and contrast detection). We used a bootstrapping technique to assess the significance of individual correlations as well as the differences between correlations (Efron & Tibshirani, 1993).

To compute the error of the correlation coefficients we first randomly resampled with replacement 10,000 times from the TOWRE scores and psychophysical thresholds (14 scores and 14 thresholds in each sample). We computed the correlation coefficient for each sample, generating a distribution of r values with a mean of zero. To determine the statistical significance of individual correlations, we calculated the percentile of each correlation coefficient in

relation to the above distribution of r values. The p values reported indicate the probability that a correlation coefficient is different from zero.

We also assessed the significance of differences between adult and child correlations. To do so we combined the TOWRE scores and psychophysical thresholds of adults and children into union distributions. We resampled randomly with replacement 10,000 times from the union distributions (14 scores and 14 thresholds in each sample) then computed the correlation coefficients and the differences between adult and child coefficients for each sample. The resulting difference values were centered on zero and represented a distribution where H_0 is true. Using the original data, we found the percentiles for the difference values on the resampled distribution. Reported p values represent the probability that correlation coefficients are from two different distributions.

3. Results

3.1. TOWRE and WASI performance

The TOWRE raw scores for the SWE and PWE subtests were converted to age-normed standard scores. The standard scores were averaged across forms A and B for each participant, producing a composite score with a mean of 100 and standard deviation of 15. On the SWE subtest adults had a performance range from 73 to 113 with a mean score of 96, ($SD = 11$). Performance on the PWE showed a similar range, 72–120 ($M = 104$, $SD = 14$). Children's scores were more variable, ranging between 56–145 ($M = 101$, $SD = 21$) on the SWE and 61–144 ($M = 101$, $SD = 23$) on the PWE. Overall, the TOWRE data showed a broad range of standard scores. Adults had scores within ± 2 SD of the mean of the standard distribution, children within ± 3 standard deviations.

Analysis of WASI data involved computing T scores ($M = 50$, $SD = 10$) for the Vocabulary and Matrix Reasoning subtests. Adults showed a range of 41–77 ($M = 64$, $SD = 9$) for the Vocabulary subtest, 50–70 ($M = 61$, $SD = 5$) for the Matrix Reasoning. Children's scores ranged from 36 to 73 ($M = 58$, $SD = 10$) for Vocabulary, 48–76 ($M = 61$, $SD = 8$) for Matrix Reasoning. A composite, full-scale intelligence quotient (FSIQ) was calculated from the subtests. All participants showed average or above average intelligence: children ($M = 117$, $SD = 14$), adults ($M = 118$, $SD = 11$).

3.2. Psychophysical thresholds

3.2.1. Speed discrimination

Adults showed better performance than children on the speed discrimination task (Fig. 2). This was true in all three analyses: 1. *QUEST median value*: When speed discrimination thresholds (Weber fraction) were computed as the median of the QUEST run, thresholds were 3× higher in children (0.36) than in adults (0.13). 2. *Fitted slope*: Fitting the slope to each observer and allowing threshold and slope to vary produced similar thresholds (children: 0.30; adults: 0.12). 3. *Median intensity*: Calculating thresholds as the median value over all experimental trials in each observer also confirmed previous analyses (children: 0.29; adults: 0.11). These results indicate that our basic finding does not depend the methods used in threshold estimation.

3.2.2. Contrast detection

We found no difference in contrast thresholds between children and adults. Both naïve children and adults performed well on the contrast detection task with thresholds reaching those of experienced psychophysical observers (1% thresholds; Fig. 2). When contrast detection thresholds were computed as the median of the QUEST run, the analysis did not reveal an appreciable difference

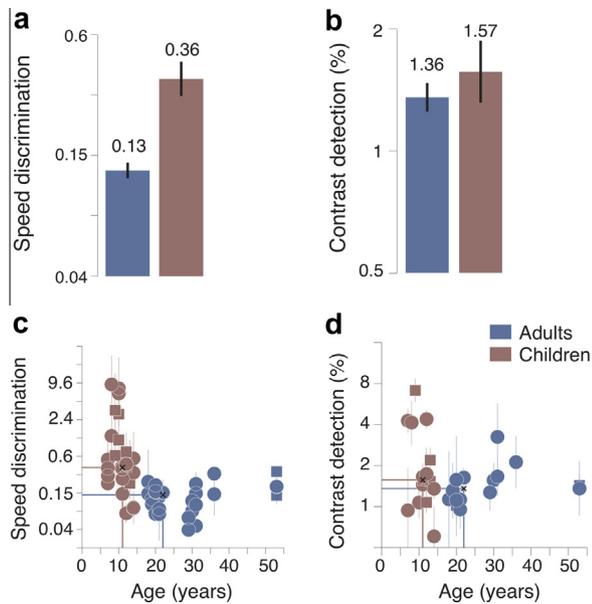


Fig. 2. Speed discrimination and contrast detection thresholds. a and b. Bar graphs of speed discrimination and contrast detection thresholds. a. Median \pm SEM speed discrimination thresholds (Weber fraction) in adults and children. b. Median \pm SEM contrast detection thresholds (%) in adults and children. c and d. Scatter plots of participants' age and the psychophysical thresholds. c. Speed discrimination thresholds \pm 1 SD. d. Contrast detection thresholds \pm 1 SD. For speed discrimination, two thresholds were measured for each participant with gratings of slightly different contrast (16% and 24%). Intersecting blue and red lines mark mean values for each group of participants. *Legend:* Adults = Blue. Children = Red. Circles = Normal Readers. Squares = Developmental Dyslexia. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

in the median thresholds (children, 1.57; adults, 1.35). Fitting the slope of each observer produced similar values (children, 1.46; adults, 1.22), as did the median intensity analysis (children, 2.67; adults, 1.51).

3.2.3. Thresholds and age

To evaluate how speed discrimination and contrast detection change with development, we correlated the mesopic thresholds with participant age. We found that both speed discrimination and contrast detection thresholds were significantly correlated with participant age (Fig. 2). Children showed significant negative correlations between the thresholds and age: older children having lower thresholds than younger children (speed discrimination: $r = -0.34$, $p = .01$; contrast detection: $r = -0.42$, $p = .04$). In contrast, adults showed positive correlations, older adults having slightly higher thresholds than younger adults (speed discrimination: $r = 0.28$, $p = .03$; contrast detection: $r = 0.31$, $p = .02$).

3.3. Psychophysical thresholds and psychological test correlations

3.3.1. Speed discrimination and reading rate

Both children and adults showed a negative relationship between real word reading rate and speed discrimination. Higher scores on the Sight Word Efficiency (SWE) section of the TOWRE were associated with lower speed discrimination thresholds. This relationship was statistically significant in both children, $r = -0.37$, $p = .02$, and adults, $r = -0.52$, $p = .001$ (Fig. 3, panel a). Bootstrapping the difference revealed correlation coefficients were not significantly different between adults and children ($p = .58$).

We tested whether there was a similar relationship between speed discrimination performance and the Phonemic Decoding Efficiency (PDE) or pseudo-word scores. There were negative rela-

tionships between speed discrimination thresholds and pseudo-word reading rates. However, correlations were non-significant in both children, $r = -0.16$, $p = .21$ and adults, $r = 0.08$, $p = .47$ (Fig. 3, panel c). In addition, there was no significant difference between adult and child correlation coefficients ($p = .21$).

3.3.2. Contrast detection and reading rate

Contrast detection thresholds did not correlate with single-word reading rates. This was true for real words (children: $r = -0.38$, $p = .07$; adults: $r = -0.10$, $p = .29$; Fig. 3, panel b) and pseudo-words (children: $r = -0.31$, $p = .09$; adults: $r = 0.31$, $p = .07$; Fig. 3 panel d). Adult and child correlation coefficients were not significantly different for SWE ($p = .27$) and PDE ($p = .11$) subtests.

3.3.3. Psychophysical thresholds and WASI test scores

Our analysis did not find relationships between the WASI test scores and either speed discrimination or contrast detection (Fig. 4). Speed discrimination was not significantly correlated with the Vocabulary (adults: $r = 0.12$, $p = .41$; children: $r = -0.20$, $p = .11$) or Matrix Reasoning (adults: $r = -0.15$, $p = .27$; children: $r = -0.08$, $p = .45$) scores. Correlations with contrast detection were also non-significant: Vocabulary (adults: $r = 0.28$, $p = .14$; children: $r = -0.20$, $p = .16$), Matrix Reasoning (adults: $r = 0.28$, $p = .07$; children: $r = -0.07$, $p = .44$).

4. Discussion

We acquired mesopic thresholds (speed-discrimination and contrast-detection) and reading rates in participants with a wide range of reading skills. We found two main results related to the threshold measurements: 1. Speed discrimination thresholds are lower in adults than in children, but there is no reliable group difference for contrast detection. 2. Speed discrimination and contrast detection thresholds are negatively correlated with age in children but positively correlated with age in adults. Younger children and older adults have higher (speed discrimination and contrast-detection) thresholds. Young adults have the lowest thresholds – the best visual performance.

We calculated correlation coefficients between the visual thresholds and reading rates. Speed discrimination thresholds are negatively correlated with real word reading rates in adults and children. Participants with lower speed discrimination thresholds have faster real word (SWE) reading rates. This correlation is more robust for adults ($r = -0.52$) than children ($r = -0.37$). Conversely, we found no significant correlations between speed discrimination thresholds and pseudo-word (PDE) reading rates. We also found no correlations between reading rates and contrast detection thresholds or reading rates and the WASI subtest scores.

Our results demonstrate that: 1. Speed discrimination thresholds correlate with reading rates. Contrast detection thresholds do not. 2. Speed discrimination thresholds correlate with the reading rates of familiar, real words but not pseudo-words. 3. Finally, speed discrimination does not correlate with cognitive measures orthogonal to reading rate like analytical reasoning and vocabulary.

4.1. Speed discrimination and word familiarity

Our data show that speed discrimination thresholds are correlated with reading rates for actual words (SWE) but not pseudo-words (PDE). Both sets of stimuli are pronounceable, share words of similar length and complexity, yet they differ in their familiarity. Common experience confirms real words are more familiar. Participants have likely encountered the actual word “understand” in

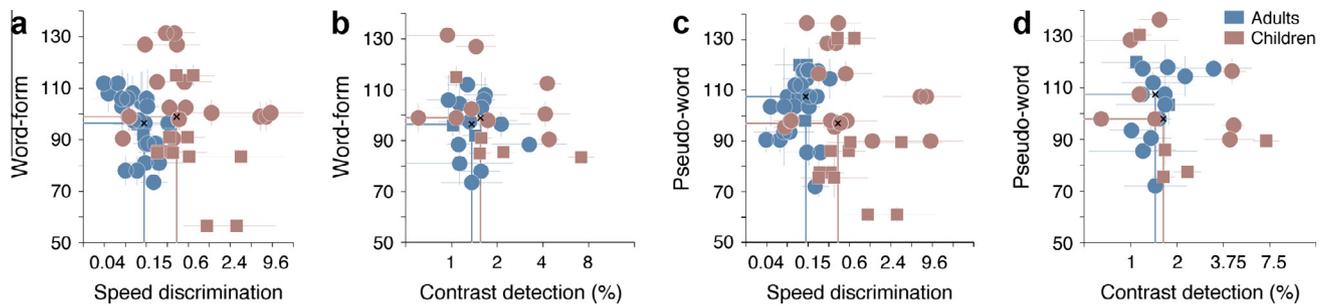


Fig. 3. Correlation between reading rates, speed-discrimination and contrast detection thresholds. a and b. Scatterplots of real word reading scores and psychophysical thresholds. a. Speed discrimination. b. Contrast detection. c and d. Scatterplots of pseudo-word reading scores and psychophysical thresholds. c. Speed discrimination. d. Contrast detection. All plots are lin-log. Error bars indicate ± 1 SD. Vertical lines mark the median speed/contrast thresholds for each group of participants; adults and children. Horizontal lines mark the median reading score.

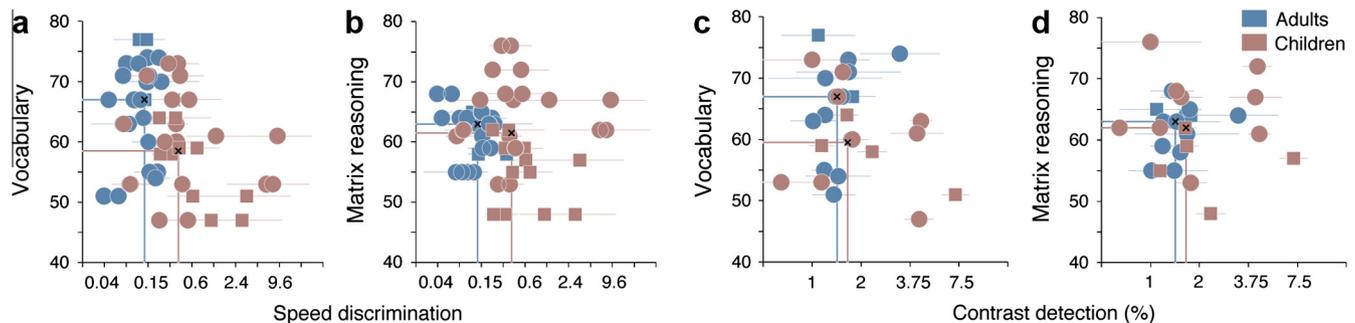


Fig. 4. No correlation between WASI scores, speed-discrimination and contrast detection thresholds. a and b. Scatter plots of speed-discrimination thresholds and WASI scores a. Vocabulary. b. Matrix Reasoning. c and d. Scatter plots of contrast detection thresholds and WASI scores. c. Vocabulary. d. Matrix Reasoning. All plots are lin-log. Error bars indicate ± 1 SD. Vertical lines mark the median speed/contrast thresholds for adults and children. Horizontal lines mark the median test score.

print before but not the pseudo-word “fermabalt”. In models of word recognition, word representations are constructed by identifying spatial relationships among letters (Dehaene et al., 2005; Grainger et al., 2006; Whitney, 2001). Word familiarity may affect this process. The finding of a dissociation between SWE and PDE correlations indicates that familiarity is a factor in magnocellular operations that may influence reading rate.

These findings also evidence position encoding as a potential mechanism. Frequently encountering the same words may draw attention to specific identifiers, such as the first and last letter, as well as internal letter pairings (Bouma, 1973; Bouwhuis & Bouma, 1979). Cornelissen and Hansen (1998) and Cornelissen et al. (1998a) theorize that visual identification of words depends on attention to the spatial relationships among the letters. Inability to do so results in “letter errors”, instances where words are mispronounced due to confusion over letter positions. They noticed this effect in children learning to read. The better readers in their sample demonstrated significantly less letter errors. It may be that continued experience with vocabulary tunes position encoding to a familiar orthography.

We interpret the current results similarly. The SWE task is correlated with speed discrimination because reading real words engages mechanisms specific to frequently encountered stimuli. The SERIAL model, for example, proposes that repeated attention to common letter combinations yields automatic word recognition (Whitney, 2001; Whitney & Cornelissen, 2005). In this way the magnocellular pathway may become primed to recognize familiar words. In contrast, pseudo-word reading may occur in a more laborious or all together different manner, where words are processed letter-by-letter (Coltheart et al., 2001). Consequently, reading actual words reveals inter-individual differences that are not real or resolvable with PDE task.

Our findings are consistent with a longstanding experimental literature demonstrating word familiarity effects in reading and lexical tasks. More familiar words have faster naming and lexical decision times (Balota & Chumbley, 1984; Cattell, 1886; Forster & Chambers, 1973; Howes & Solomon, 1951; Monsell, Doyle, & Haggard, 1989; Solomon & Postman, 1952). Our data also complement evidence that letter position and spatial relationships influence word recognition. The word superiority effect (WSE), for example, demonstrates letters are more quickly identified within the context of a word than alone or among random letter strings (Johnston & McClelland, 1973; Reicher, 1969; Wheeler, 1970). Other findings show letter strings prime recognition if they share letters in the same position as subsequent words (Grainger & Jacobs, 1996; Humphreys, Evett, & Quinlan, 1990; Peressotti & Grainger, 1995).

Other aspects of our data demonstrate age differences in visual ability. We found that both speed discrimination and contrast detection improve as children grow older but decline in late adulthood. These findings broadly agree with developmental studies on children which show performance on visual tasks improves substantially between 4 and 7 years of age (Lovegrove, Heddle, & Slaghuis, 1980; Slaghuis & Ryan, 1999). In addition, reports indicate a slowing of visual processing as adults age. It often takes longer for older adults to detect, discriminate, and identify visual targets compared to young adults (for a review see Owsley, 2011). One interpretation of our findings is that the development and aging of neural circuitry is an influence on visual performance.

The dissociation between SWE and PDE correlations may not solely be due visual processes though. The recognition of real words could be visual and automatic, but reading unfamiliar words may require an analysis of phonology. Coltheart et al. (1993, 2001), for example, argue for a hard-wired distinction between lexical

and pseudo-lexical reading in their Dual-Route Cascaded (DRC) model. In the lexical route, familiar words are recognized at a glance and directly activate established phonological and semantic representations. In the pseudo-lexical route, unfamiliar words are sounded-out through grapheme-to-phoneme correspondence rules. Within this framework, our findings on the SWE subtest may primarily demonstrate individual differences in visual processing. In contrast, the PDE subtest measures an interaction between both visual and phonological processes. Consequently a visual task like speed discrimination is correlated with reading real words but not pseudo-words.

Finally, we found no relationships between the visual thresholds and psychometric measures related to general cognitive abilities. Neither speed discrimination or contrast detection tasks are correlated with WASI Vocabulary and Matrix Reasoning subtests in children or adults. From the standpoint of a visual interpretation, these results make sense. If speed discrimination is an index of magnocellular processing, it should not correlate with measures of verbal and analytical intelligence. These measures are more likely influenced by developmental stage in children and overall education in adults.

4.2. Speed discrimination, not contrast detection, predicts reading rate

We found speed discrimination to be an effective predictor of reading performance. The relationship between speed discrimination thresholds and reading rates in our sample complement a large literature demonstrating motion sensitivity is correlated with reading ability (Cornelissen & Hansen, 1998; Demb, Boynton, Best, et al., 1998; Demb, Boynton, & Heeger, 1998; Schulte-Körne, Bartling, Deimel, & Remschmidt, 2004; Solan, Hansen, Shelley-Tremblay, & Ficarra, 2003; Talcott et al., 2000, 2002, 2003; Wilmer et al., 2004; for a review see Benassi et al., 2010).

Researchers assess motion sensitivity in different ways. In motion coherence tasks participants view random dot kinematograms (RDK). They attempt to detect the direction of coherently moving dots embedded in a larger, randomly moving set. In speed discrimination tasks participants judge the relative velocity of two consecutively presented gratings. Among motion-based tasks, the most used index is motion coherence. Benassi et al. (2010) performed a meta-analysis on 53 studies comparing motion perception in normal and impaired readers. All employed measures of motion coherence. Exceptions using speed discrimination include studies by Demb, Boynton, Best, and Heeger (1998) and Demb, Boynton, and Heeger (1998), Wilmer et al. (2004) and Ramus et al. (2003).

Wilmer et al. (2004) used exploratory factor analysis to show that motion coherence is correlated with reading accuracy while speed discrimination is correlated with reading rate. The authors go on to argue that speed discrimination is perhaps a better index of reading performance in normal readers. Our findings support this. We obtained a moderate correlation for adults ($r = -0.52$) and a more modest correlation for children ($r = -0.37$), but both are larger than the average effect size for motion coherence ($d = 0.19$) (Benassi et al., 2010).

Where motion coherence measures an observer's ability to integrate global visual information amid noise, speed discrimination involves local, spatial comparisons. We tasked participants to judge the velocities of drifting gratings presented to the same visual location. This fact may explain our higher than average correlations. If word recognition requires local analysis of letter combinations, then speed discrimination may have greater validity as a reading index, particularly for reading rate.

We did not find correlations between contrast detection and reading rate. Some studies have demonstrated reduced contrast performance among poor readers (i.e., dyslexics), particularly for

stimuli with low spatial and high temporal frequencies (Borsting et al., 1996; Edwards et al., 2004; Evans et al., 1994; Felmingham & Jakobson, 1995; Lovegrove et al., 1982; Martin & Lovegrove, 1984, 1987; Mason et al., 1993). Others have failed to find such differences (Ben-Yehudah et al., 2001; Cornelissen et al., 1995; Gross-Glenn et al., 1995; Hayduk et al., 1996; Williams et al., 2003).

Demb, Boynton, Best, et al. (1998) found motion perception to be a better predictor of reading performance than contrast detection. They suggest that variability in the literature is explained by not effectively controlling luminance. Vision at low luminance involves signaling in a small number of photoreceptors, specifically rods (Field, Sampath, & Rieke, 2005). Reducing luminance during a visual task can isolate neural pathways. Parvocellular (P) cells do not respond to visual patterns with a mean retinal illuminance below 0.43 photopic trolands (td) (Purpura, Kaplan, & Shapley, 1988). This means the M pathway primarily transmits information in mesopic and scotopic light conditions.

The current study kept mean luminance low (4 cd/m^2) to emphasize the magnocellular pathway inputs to cortex. Our results agree with Demb, Boynton, Best, et al. (1998). Absence of correlations with contrast detection suggest contrast sensitivity is not a magnocellular influence on reading rates, at least when the text contrast is high and the readers have normal vision.

4.3. Neurocorrelates of word recognition

Efficient reading requires coordination between oculomotor and object recognition processes (Vidyasagar & Pammer, 2010). These functions are thought to be supported by separate neural routes: the dorsal and ventral visual streams (Goodale & Milner, 1992). Magnocellular neurons dominate the dorsal stream (Merigan, Nealey, & Maunsell, 1993), which interprets the motion and spatial information generated during visual scanning (Tootell et al., 1995). The ventral stream, in contrast, deals in object recognition including the identification of written words (Grill-Spector, Kushnir, Hendler, & Malach, 2000; McCandliss, Cohen, & Dehaene, 2003).

Dorsal stream sites include the temporo-parieto-occipital junction, also known as area MT. Anatomical studies in non-human primates show the majority of fibers that innervate MT are magnocellular (DeYoe & Van Essen, 1988; Maunsell & Newsome, 1987). Lesions of MT in monkeys increases motion coherence thresholds (Newsome & Pare, 1988). Similar damage in human results in deficits of motion perception and oculomotor control (Vaina, Lemay, Bienfang, Choi, & Nakayama, 1990). Functional MRI studies of healthy humans reveal judgments of coherent motion, speed discrimination, and other motion-based tasks activate area MT (Braddick, O'Brien, Wattam-Bell, Atkinson, & Turner, 2000; Braddick et al., 2001; Buchel et al., 1998; Chawla, Phillips, Buechel, Edwards, & Friston, 1998; Culham, He, Dukelow, & Verstraten, 2001; Haug, Baudewig, & Paulus, 1998; Howard et al., 1996; Tootell et al., 1995).

Area MT has also been linked to reading achievement. Functional MRI studies of dyslexics report less activation in MT compared to controls (Demb et al., 1997) or no activation at all (Eden et al., 1996). Perturbation of MT by transcranial magnetic stimulation (TMS) decreases reading performance in non-word naming tasks (Liederman et al., 2003). The authors suggests this pattern of performance indicates MT contributes to letter localization. Application of repetitive TMS to the right posterior parietal cortex, an area adjacent to MT, disrupts word naming in proficient readers (Braet & Humphreys, 2006). Interestingly, this effect was greater for mixed-case words than lowercase words. The authors suggest the right parietal lobe, which is part of the dorsal stream, supports word recognition in unfamiliar formats.

The dorsal stream and area MT may also indirectly affect word recognition and reading rate via communication with the ventro-temporal cortex. The visual word form area (VWFA), a region situated on the fusiform gyrus, is thought to process word-forms before associations with phonology and semantics (McCandliss et al., 2003). Though the VWFA is located within the ventral visual stream, it likely receives input from dorsal cortex. Structural evidence of this connection is the ventral occipital fasciculus (VOF), a white matter tract connecting the dorsal and ventral cortices of the occipital lobe (Déjerine, 1895). Recently Yeatman, Rauschecker, and Wandell (2013) demonstrated that fascicles within the VOF connect the functionally-defined VWFA with occipital and dorsomedial cortex.

The identification of orthography is a specific case of object recognition, and recent fMRI experiments evidence communication between dorsal and ventral streams during object recognition (Grill-Spector, Kushnir, Edelman, Itzhak, & Malach, 1998; Grill-Spector et al., 2000; Kriegeskorte et al., 2003; Konen & Kastner, 2008). Levy, Walsh, and Lavidor (2010) theorize that the dorsal stream may speed word recognition by sending an initial, low-pass representation of a word to the VWFA where it is further processed. If this initial representation is stalled or impoverished, it may result in delays that ultimately affect reading rate.

The current study cannot affirm or refute biological models of reading performance. However, our results are consistent with brain and behavioral data showing dorsal stream function and reading performance are related. The finding that processing in the right parietal cortex is affected by mixed-case words suggests this area is sensitive to familiar orthography (Braet & Humphreys, 2006). Other findings indicate area MT is involved in letter localization (Liederman et al., 2003). It is unknown though if MT or parietal operations could be described as position encoding. Also unknown is whether area MT and other components of the dorsal stream evaluate orthography alone or in conjunction with ventro-temporal cortex. Further research is necessary to thoroughly evaluate potential neurocorrelates of word familiarity effects.

4.4. Limitations

The current findings support the theory that magnocellular processing contributes to reading rate. The pattern of results suggests position encoding as a mechanism, not contrast sensitivity. However, this report cannot address other ways the M pathway may influence reading performance. Magnocellular processes may contribute to reading through the coordination of visual functions like selective attention, oculomotor control, and foveal/parafoveal interaction (Boden & Giaschi, 2007).

Some reading difficulties may stem from deficits in saccadic eye movements or binocular fixation (Pavlidis, 1981; Stein & Fowler, 1993). Weak M pathway input to oculomotor centers is a potential cause of this problem (Fischer & Hartnegg, 2000; Stein & Walsh, 1997). Lesions to MT, for example, disrupt saccades and the visual tracking of moving objects (Leigh & Zee, 1999). Erratic saccade patterns have been found in dyslexics, evidencing their role in reading impairment (Lennerstrand, Ygge, & Jacobson, 1993; Poblano, de Caballero, Castillo, & Cortes, 1996; Rubino & Minden, 1990).

Another possibility is the M pathway contributes to reading through the allocation of visual attention. During reading the focus of attention often evaluates text beyond fixation. Operations of covert attention filter this information so that text to the left of fixation or outside the line of interest does not disrupt word recognition. The posterior parietal cortex (PPC) is a likely neurocorrelate for this process. The PPC receives a majority of its input from the M pathway and damage to it affects the ability to disengage attention (Posner, Walker, Friedrich, & Rafal, 1984). Some patients with

PPC lesions, for example, demonstrate neglect dyslexia, a condition where letters at the beginning of a word or the words at the beginning of a line are ignored (Brunn & Farah, 1991; Riddoch, Humphreys, Cleton, & Fery, 1990).

A final consideration is how the visual system incorporates information from the parafovea during reading. The parafovea accesses the visual field surrounding fixation (fovea). It can evaluate low spatial frequency information such as word length, shape, as well as beginning and end letters (Rayner, Inhoff, Morrison, Slowiaczek, & Bertera, 1981; Rayner, Well, Pollatsek, & Bertera, 1982). Parafoveal vision facilitates processing of local information from the fovea. If impaired, the M pathway could decrease sampling from the parafovea and compromise subsequent visual analyses and fixations (Lehmkühle, 1993; Lehmkühle, Garzia, Turner, Hash, & Baro, 1993).

The above are all ways the M pathway could influence reading. Importantly, they are not mutually exclusive. Each could act on visual information in parallel but at different levels of analysis. Our data suggest familiar orthography is a contributing factor to reading rate. Theories of position encoding accommodate this finding, but they also reference attention as a mechanism of action (Whitney, 2001). In addition, position encoding of parafoveal information could contribute to word recognition and guidance of saccades. We suggest the current evidence supports position encoding, but acknowledge further research is necessary to understand how other mechanisms of the M pathway may influence or direct this process.

Another caveat regarding our findings is they are correlational. We found significant correlations, for example, between the psychophysical thresholds and age. This may evidence the aging of neural circuitry. However, correlations preclude causal interpretation. An alternative possibility is that reading experience could drive biological change. It is known, for example, that the development of reading skills enhances early visual processes like contour integration (Szwed, Ventura, Querido, Cohen, & Dehaene, 2012). It is plausible then that extensive reading experience changes the allocation of attention and visual speed of processing for orthography. In fact, the trained allocation of attention to specific letter combinations is an essential component of the SERIOL model (Whitney, 2001).

Our results demonstrate a relationship between magnocellular function and reading performance, but further research is necessary to understand how reading experience and the M pathway could interact. An experimental way to study this could be to train visual observers on tasks that enhance magnocellular capabilities while periodically measuring reading rates (see Chouake, Levy, Javitt, & Lavidor, 2012). This design may be best suited to adult, skilled readers since their reading performance is stable. If the training tasks address different aspect of magnocellular processing (i.e., oculomotor, covert attention, parafoveal/foveal interaction) they may reveal the variance each contributes to reading performance.

Finally, it is worthwhile to consider our data in reference to dyslexia. Our sample included normal and poor readers but less than half were diagnosed dyslexics (11). Consistent with previous work, we found that dyslexics largely reside at the lower end of the performance distributions for both reading and speed discrimination (Demb, Boynton, Best, et al., 1998; Hansen, Stein, Orde, Winter, & Talcott, 2001; Kevan & Pammer, 2008; Ramus et al., 2003; Ridder, Borsting, & Banton, 2001; Slaghuys & Ryan, 1999; Talcott, Hansen, Assoku, & Stein, 2000; Talcott et al., 1998; Witton et al., 1998).

However, not all researchers have found such differences (Kronbichler, Hutzler, & Wimmer, 2002; Williams et al., 2003) and some reports have found impaired motion sensitivity in certain dyslexic subtypes but not others (Ramus et al., 2003;

Slaghuys & Ryan, 1999). There seems to be substantial heterogeneity among dyslexics with visual/magnocellular impairments, including some individuals with no deficit at all. The reason for this is the source of considerable debate. Many researchers maintain that dyslexia is principally a disorder of phonology and that visual deficits are simply epiphenomena. Variability in experimental findings attests to the complexity of the issue (Farmer & Klein, 1995; Handler & Fierston, 2011; Olulade, Napoliello, & Eden, 2013; Ramus & Ahissar, 2012; Skottun, 2000; Stein, 2001).

While we included dyslexics in our sample, our design and analysis does not permit statements on the causal factors of dyslexia. Recent intriguing longitudinal studies find that motion sensitivity in pre-literate children predicts orthographic performance (Boets, Wouters, van Wieringen, & Ghesquiere, 2006) and precedes the diagnosis of dyslexia in some cases (Boets, Vandermosten, Cornelissen, Wouters, & Ghesquiere, 2011). However, magnocellular function may affect reading performance in both dyslexics and abled readers, but this does not mean magnocellular dysfunction causes dyslexia. From our findings, we suggest speed discrimination may have utility in examining motion sensitivity and its relation to reading fluency, but we do not claim it differentiates dyslexics from normal readers or implicates a specific cause.

5. Conclusions

We believe the current results have valuable implications for reading research and directions for further study. First, the findings here afford another example of research implicating the magnocellular pathways in skilled reading. Many previous reports have used motion coherence as a standard measure of the M pathway and an index of reading performance. Few studies have employed speed discrimination to the same ends. Here we demonstrate the utility of speed discrimination and find it yields stronger correlations than the average effect size for motion coherence.

Secondly, we found that speed discrimination is correlated with some reading rates (real word/SDE) but not others (pseudo-word/PDE). This finding suggests speed discrimination indexes operations of the magnocellular pathway that aid word recognition and reading rate. Because word familiarity is a factor, we submit these operations may involve an analysis of letter position. The lack of any correlation with contrast detection suggests contrast sensitivity is not a factor in word recognition and reading rate.

Finally, we agree with Wilmer et al. (2004) that speed discrimination may be a more subtle test of reading performance, capable of differentiating skill level in normal readers. Because of this, we believe it could also be successful in clarifying the spectrum of visual performance found among the reading impaired. We suggest the selective correlation between speed discrimination and reading rate needs further investigation, especially in relation to the early prognosis of reading impairments.

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