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Assessing the role of different spatial frequencies in word perception by good and poor readers

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Numerous studies indicate that dyslexic and nondyslexic individuals exhibit different patterns of sensitivity to spatial frequency. However, the extension of this effect to normal (nondyslexic) adults of good and poor reading abilities and the role played by different spatial frequencies in word perception have yet to be determined. In this study, using normal (nondyslexic) adults, we assessed reading ability, spatial frequency sensitivity, and perception of spatially filtered words and nonwords (using a two-alternative forced choice paradigm to avoid artifactual influences of nonperceptual guesswork). Good and poor readers showed different patterns of spatial frequency sensitivity. However, no differences in accuracy of word and nonword perception were found between good and poor readers, despite their differences in spatial frequency sensitivity. Indeed, both reading abilities showed the same superior perceptibility for spatially filtered words over nonwords across different spatial frequency bands. These findings indicate that spatial frequency sensitivity differences extend to normal (nondyslexic) adult readers and that a range of spatial frequencies can be used for word perception by good and poor readers. However, spatial frequency sensitivity may not accurately reveal an individual's ability to perceive words.

A substantial body of psychophysical evidence indicates that the human visual system operates in the spatial frequency domain, responding to visual patterns on the basis of their spatial frequency content. Sensitivity to various spatial frequencies is known to vary systematically (e.g., Campbell & Robson, 1968; Graham, 1989). In particular, the amount of contrast (i.e., contrast threshold) necessary for the perception of static bars whose luminance is modulated sinusoidally about a fixed mean level is known to vary as a function of their spatial frequency. The reciprocal of contrast threshold is contrast sensitivity. Graphical representation of variation in contrast sensitivity over a range of spatial frequencies describes the contrast sensitivity function (CSF). In general, the human visual system is most sensitive to spatial frequencies in the range of 2–6 cycles per degree (cpd), and more contrast is needed for detection of lower and higher spatial frequencies.

Numerous researchers have found that dyslexic and nondyslexic controls exhibit different patterns of sensitivity to spatial frequencies (e.g., Borsting et al., 1996; Cornelissen, 1993; Demb, Boynton, Best, & Heeger, 1998; Evans, Drasdo, & Richards, 1993, 1996; Gross-Glenn et al., 1995; Lovegrove, Bowling, Badcock, & Blackwood, 1980; Lovegrove et al., 1982; Martin, Cornelissen, Fowler, & Stein, 1993; Martin & Lovegrove, 1984, 1988). In particular, studies indicate that dyslexic individuals have reduced sensitivity to certain spatial frequencies and that this reduction tends to be greatest in the low- to mid-frequency range (i.e., between 2 and 8 cpd; Borsting et al., 1996; Cornelissen, 1993; Demb et al., 1998; Evans et al., 1993, 1996; Lovegrove et al., 1980; Lovegrove et al., 1982, Experiment 2; Martin & Lovegrove, 1984, 1988; see Skottun, 2000, for a review).

It remains to be seen whether this sensitivity difference between dyslexic and nondyslexic controls extends to normal (i.e., nondyslexic) adult readers. Unfortunately, studies in which spatial frequency sensitivity differences between normal adult readers of good and poor reading ability have been examined are rare, and the issue is far from resolved. However, one possibility is that the sensitivity differences found between dyslexic and nondyslexic controls represent a distinct disorder that is specific to this reading-disabled population (Rutter & Yule, 1975). Alternatively, the reduced sensitivity of dyslexic individuals to various spatial frequencies may represent the lower end of a normal continuum (Au & Lovegrove, 2001; Cornelissen et al., 1998) and, so, extend to the normal adult

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population. Accordingly, one aim of the present study was to assess the reading ability of normal adult readers and determine whether adults of good and poor reading ability show different patterns of spatial frequency sensitivity.

A second aim of this study was to explore the role of different spatial frequencies in reading by examining directly the effectiveness of different spatial frequencies in word perception. Although words might be considered to be made up only of local structural features (e.g., oriented line segments, terminators, and angles), words can be described in terms of their spatial frequency content. In psychophysical terms, words are complex images comprising a broad range of spatial frequency information—from coarse scale (i.e., low spatial frequency) information describing the overall extent of the words to more fine scale (i.e., high spatial frequency) information necessary to specify the individual letters and letter features (see Ginsburg, 1980, 1986, for further discussion). Moreover, this general description of words maps onto convincing psychophysical and anatomical evidence of spatial-frequency-selective pathways in the human visual system (e.g., Blakemore & Campbell, 1969; Campbell & Robson, 1968). However, few studies have directly examined the role of different spatial frequencies in word perception, and none has contrasted the ability of good and poor readers to use the spatial frequency information contained in words.

Yet it is possible to remove different spatial frequencies from words in order to restrict their spatial frequency content (Leat & Munger, 1994; Legge, Pelli, Rubin, & Schleske, 1985; see also Jordan, Thomas, & Patching, 2003; Jordan, Thomas, Patching, & Scott-Brown, 2003). For instance, Legge, Pelli, et al. (1985) used a visual filter to remove high spatial frequencies from text and found that reading rate remained unaffected, relative to that for unfiltered text. On these grounds, Legge, Pelli, et al. suggested that just one low spatial frequency band is sufficient for reading. In a similar vein, Leat and Munger (1994) filtered text into narrow (octave-wide) bands of spatial frequencies with varying center frequencies. They found that participants were able to read text equally well when only high spatial frequencies remained, when only medium spatial frequencies remained, and when only low spatial frequencies remained, indicating that a broad spectrum of spatial frequency information may be used in reading.

However, when participants are required simply to read frequency-filtered text, it is impossible to determine whether the spatial frequencies under investigation are sufficient for word perception, because participants may artifactually enhance their performance by correctly guessing the identities of words, using partial word information and other contextual cues (Jordan & Thomas, 2002). For example, Jordan and Thomas pointed out that when reading sentences, participants can use explicit knowledge of sentence content and structure (termed *sentential* constraint) and explicit knowledge of how words are spelled (termed *lexical* constraint), and these two sources of nonperceptual information may enhance reading performance. Therefore, in studies in which participants are required to read spatially filtered text, measures of word *perception* may be contaminated, because participants are able to augment their performance by guessing the identities of words, using contextual cues and partial word information. In particular, the effect of filtering text may be reduced because words can be guessed using sentential and lexical constraint, and this influence may be particularly beneficial when text is difficult to process perceptually. Consequently, without appropriate controls, it is difficult to determine the *perceptual* role of different spatial frequencies in word perception. As Jordan and Thomas pointed out, a crucial step toward assessing the perceptibility of words is to examine word perception under conditions that suppress the ability of sentential and lexical constraints to enhance performance.

The approach of the present study was to examine the perceptibility of filtered words and nonwords by good and poor readers, using a two-alternative forced choice (2AFC) procedure (commonly known as the Reicher–Wheeler task, after Reicher, 1969; Wheeler, 1970) to suppress artifactual influences of nonperceptual guesswork (Johnston, 1978; Jordan, Patching, & Milner, 2000; Jordan & Thomas, 2002). With this task, the participants were required to respond immediately after a brief exposure of a filtered word or nonword by way of a forced choice between two unfiltered alternatives. The two alternatives consisted of the unfiltered target stimulus and a matched foil. In each case, the matched foil differed from the target by just one critical letter, and both alternatives were equally plausible (e.g., a choice between the unfiltered alternatives *word* and *work* following the brief presentation of the filtered stimulus *word*). Consequently, the Reicher–Wheeler task provides a stringent assessment of the perceptibility of filtered stimuli, while constraining nonperceptual guessing strategies that may otherwise artifactually influence responses to perceptually degraded words.

The perceptibility of filtered nonwords was examined principally to provide a benchmark against which to assess the perceptibility of filtered words. It is well established that letters in briefly exposed stimuli can be identified more accurately in words than in nonwords (the *word–nonword effect*; Hildebrandt, Caplan, Sokol, & Torreano, 1995; Johnston, 1978; Jordan et al., 2000; Jordan, Patching, & Thomas, 2003a, 2003b; Jordan, Redwood, & Patching, 2003; Krueger, 1975; McClelland, 1976; McClelland & Johnston, 1977; McClelland & Rumelhart, 1981; Reicher, 1969; Wheeler, 1970), indicating activation of orthographic and lexical processes involved in word perception (Grainger & Jacobs, 1994, 1996; Jacobs & Grainger, 1994; Johnston & McClelland, 1980; Jordan et al., 2000; Jordan et al., 2003a, 2003b; McClelland & Rumelhart, 1981, 1988; Paap, Newsome, McDonald, & Schvaneveldt, 1982). Therefore, if word–nonword effects obtain with filtered stimuli, this would suggest that the spatial frequency information present in filtered word stimuli can activate processes of word perception. Alternatively, if perceptual accuracy is equivalent with filtered words and nonwords, this would suggest that the spatial frequency information present is used in a more general fashion for perception of any letter string.

The word and nonword stimuli used in this study were filtered into eight narrow bands of spatial frequencies, each with a different center frequency. Figure 1 shows an example of a stimulus word (*word*) filtered into the eight different spatial frequency bands.[1] Reading ability was assessed by measuring effective reading speed. Effective reading speed has been widely used to assess the reading ability of normal (nondyslexic) adults (e.g., Brown, 1981; Jackson & McClelland, 1979; Leat & Munger, 1994; Legge, Mansfield, & Chung, 2001; Legge, Pelli, et al., 1985; Legge, Rubin, & Luebker, 1987; Legge, Rubin, Pelli, & Schleske, 1985; O'Brien, Mansfield, & Legge, 2000; Whittaker & Lovie-Kitchin, 1993; see also Carver, 1990). It is defined as the speed at which the test material (i.e., short passages or sentences) is read, in words per minute, multiplied either by the number of words read correctly (Legge et al., 1987) or by participants' scores on a subsequent comprehension test (Jackson & McClelland, 1979). As was argued by Jackson and McClelland, a simple measure of reading speed fails to capture the ability of readers to understand what they have read, whereas a raw comprehension score does not indicate the efficiency with which readers are able to achieve understanding. However, effective reading speed captures both these important elements of reading, and this combined measure of speed and comprehension was selected as the index of reading ability in our study.

A comparison of patterns of performance with filtered words and nonwords for good and poor readers will shed new light on how well good and poor readers are able to use the spatial frequency information present in words. For example, if word–nonword effects obtain for stimuli at a certain spatial scale for good readers, but not for poor readers, this will suggest that good readers are able to use the information at that spatial scale more effectively for the perception of words. Alternatively, if word–nonword effects for good and poor readers do not differ, this will suggest that good and poor readers use information at that spatial scale for word perception with similar effectiveness.

A sample of normal nondyslexic adults was recruited from an English university population to take part in this study. Pilot studies indicated that this sample would contain a range of reading abilities from good to poor. This is consistent with previous studies (e.g., Jackson & McClelland, 1979) in which effective reading speed has been used to assess reading ability and in which a range of reading abilities in the normal adult population has been identified. In addition, sensitivity to spatial frequencies was measured using a spatial 2AFC task in which the participants were required to indicate on which side of a video monitor a vertical grayscale grating was presented. The QUEST staircase procedure was used to estimate each participant's contrast threshold (Watson & Pelli, 1983). This procedure has a great deal of support (e.g., King-Smith, Grigsby, Vingrys, Benes, & Supowit, 1994; Pelli & Farrell, 1994) and enabled assessment of each participant's sensitivity to a range of spatial frequen-

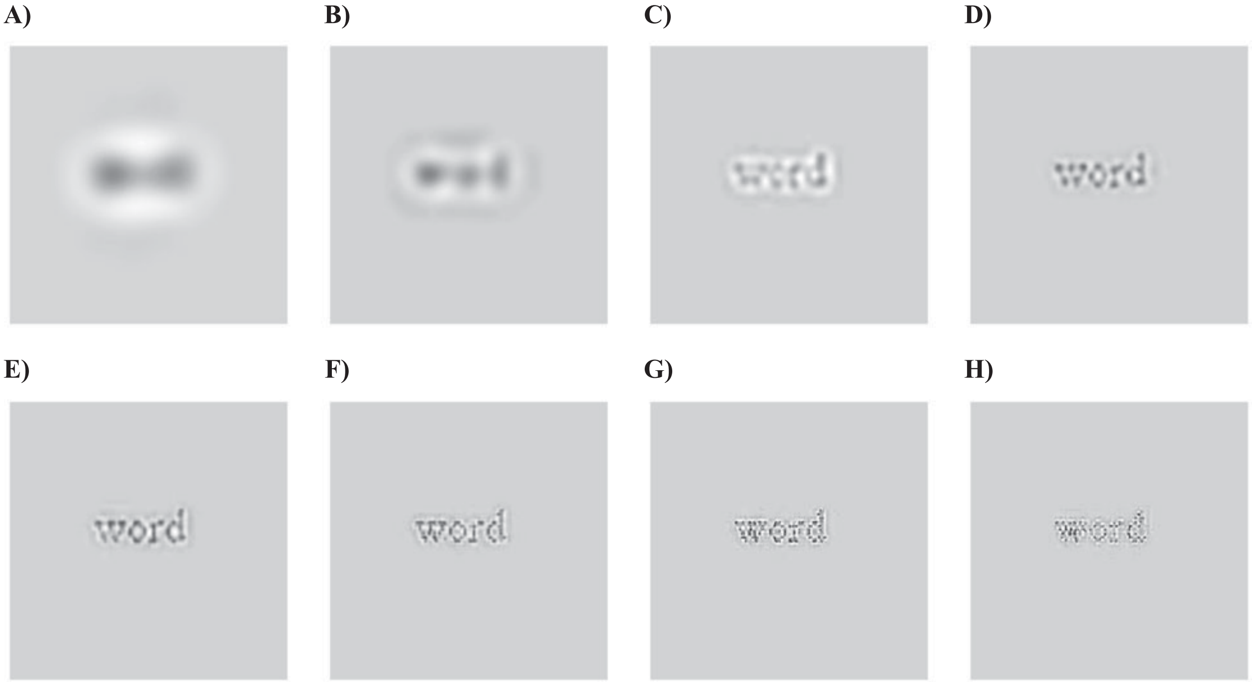

Figure 1. Example of the stimulus word *word* in the eight filtered conditions, with center frequencies of (A) 1.1, (B) 2.2, (C) 3.5, (D) 4.9, (E) 6.7, (F) 8.7, (G) 11.1, and (H) 13.7 cycles per degree/stimulus width.

cies from 0.5 to 12 cpd. Comparison of the CSFs of good and poor readers promised to reveal whether the differences in spatial frequency sensitivity found between dyslexic and nondyslexic controls extend to the normal reading adult population.

METHOD

Participants

Forty undergraduate students from the University of Nottingham took part in the experiment. All the participants were native speakers of English, and none reported any history of epilepsy or dyslexia or demonstrated any reading problems when tested. Each participant was required to take part in five 60-min sessions. In the first session, each participant was tested for visual acuity, contrast sensitivity, and reading ability. In the subsequent four sessions, perception of filtered words and nonwords was tested using the Reicher–Wheeler task.

Visual Acuity

Bailey–Lovie chart. Visual acuity was tested using the Bailey–Lovie eye chart (Bailey & Lovie, 1976). The participants were required to continue reading letters down the chart from a distance of 3 m until they failed to identify any letters on one line. Performance was scored using the method recommended by Kitchin and Bailey (1981; Reeves, Wood, & Hill, 1993). The total number of letters incorrectly read was recorded, and an *error* score of 0.02 was assigned to each; these scores were added to the last line on which any letters were read. To continue, the participants were required to have a minimum 3-m binocular acuity of -0.3 LogMAR, indicative of normal visual acuity.

Contrast Sensitivity

Stimuli. Contrast sensitivity was tested using grayscale vertical sine wave gratings of 0.5, 1, 2, 4, 6, 8, 10, and 12 cpd. These spatial frequencies were chosen to conform to previous psychophysical studies of spatial frequency sensitivity (e.g., Campbell & Robson, 1968; Ginsburg, 1986; see Graham, 1989, for a review) and to cover the range of spatial frequencies used in previous studies with dyslexic individuals (Borsting et al., 1996; Cornelissen, 1993; Demb et al., 1998; Evans et al., 1993, 1996; Lovegrove et al., 1980; Lovegrove et al., 1982; Martin & Lovegrove, 1984, 1988; see Skottun, 2000, for a review). Each vertical sine wave grating was multiplied by a circular bitmap with a Gaussian intensity profile to avoid abrupt luminance transits. A sine wave grating modulated by a Gaussian patch is termed a *Gabor stimulus* (see Figure 2). Eight Gabor stimuli, of equal size, were created, each with a different spatial frequency, so that the number of cycles (i.e., black and white bars) varied depending on spatial frequency. This procedure conforms to previous studies that have shown differences in spatial frequency sensitivity between dyslexic participants and nondyslexic controls (Borsting et al., 1996; Cornelissen, 1993; Demb et al., 1998; Evans et al., 1993, 1996; Lovegrove et al., 1980; Lovegrove et al., 1982; Martin & Lovegrove, 1984, 1988), and matches the filtered word and nonword stimuli used later in this study (see the section on image filtering below).

Visual conditions. Viewing was binocular. Gabor stimuli were presented on a gamma-corrected video monitor with a resolution of 980 × 1,024 pixels. Viewed from a distance of 57 cm, the viewable area of the monitor measured 23º horizontally and 29º vertically. Background illumination of the monitor screen and space-averaged luminance of each Gabor was kept constant at 35 cd/m^2. Each Gabor subtended 12º vertically and 12º horizontally (the radial size of each standard deviation of Gaussian patch was 3º) and was presented so that the center of each Gabor always fell 6º to the left or right of the center of the video monitor on the horizontal midline.

Apparatus. The Gabor stimuli were presented on a 40.4 × 30.2 cm Sony Trinitron GDM-F520 monitor. A Cambridge Research Systems (Rochester, Kent, U.K.) visual stimulus generator (VSG2/5) card controlled stimulus presentations and timing. Responses were collected via a Cambridge Research Systems CT3 button box. Luminance was measured using an optical photometer. The experiment was conducted in a quiet, darkened room. A viewing hood fixed to the monitor ensured a constant viewing distance and eliminated any extraneous light sources.

Design. Each different Gabor stimulus was presented 80 times, randomly interleaved, giving a total of 640 trials. Contrast sensitivity was measured using a spatial 2AFC task in which the participants had to decide on which side of the video monitor the Gabor stimulus was presented. On each trial, the contrast of each Gabor was determined using the QUEST algorithm (Watson & Pelli, 1983; see also King-Smith et al., 1994; Pelli & Farrell, 1994) in the Psychophysics Toolbox (Brainard, 1997; Pelli, 1997). The threshold was set at 0.82, and the initial contrast of each Gabor was set at the average obtained from pilot studies. The final estimate was taken as the mean of the posterior probability distribution function (after King-Smith et al., 1994).

Procedure. The participants were given written instructions informing them of the task and of the importance of responding as accurately as possible. At the start of each trial, a clearly audible beep was emitted from the button box to inform the participants that a Gabor stimulus was about to be presented. A single Gabor stimulus was then presented on either the left or the right side of the video monitor. To avoid onset transients, each Gabor was ramped on (exponentially) over the first 100 msec. Each Gabor then remained on the video monitor at the contrast level determined by the QUEST algorithm until a response was made. To make their response, the participants were required to press one of two buttons to indicate on which side of the video monitor the Gabor stimulus had been presented.

Reading Speed

Stimuli. Seven passages were selected from *Notes From a Small Island* by Bill Bryson (1995), which provided an engaging text. On average, each passage contained 527 words. Following each passage, five multiple-choice questions were presented. The questions referred to different detailed aspects of the preceding paragraph and were designed to ensure that the participants had read each paragraph in full (for further details, see Jordan, Thomas, & Patching, 2003; Jordan, Thomas, et al., 2003).

Visual conditions. Viewing was binocular. Each passage was presented on the same gamma-corrected video monitor as that used to test contrast sensitivity. The text was presented in black on a white

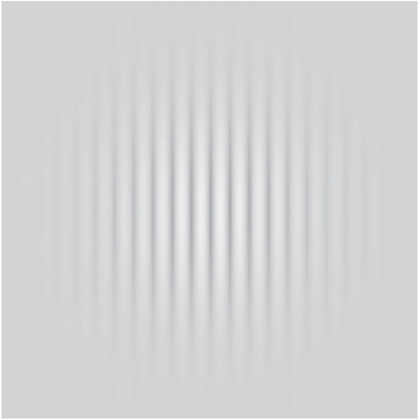

Figure 2. Example of a Gabor stimulus used in the experiment.

background, in lowercase 14-point Times New Roman font. A complete passage of text filled an area approximately 18º (horizontal) × 27º (vertical) and had proportions similar to those of an A4 page of text (which is familiar in the British reading environment). Background illumination of the monitor screen was 46 cd/m^2, and the luminance of text was 0.15 cd/m^2. Viewed from a distance of 57 cm, the average width of four letters subtended a horizontal visual angle of approximately 1º.

Design. Each participant was presented with all seven passages. One passage (always shown first) was used as practice, and the remaining six were used as test passages, shown in a random order.

Procedure. The participants were told that the experiment would examine the time taken to read different passages of text and that they should read through each passage once, from start to finish, as rapidly as if they were reading a page of a book. As soon as a button was pressed, a passage was presented (shown in its entirety on the screen), and the timer started. The participants pressed the button again when they had read the final word of each passage, and this stopped the timer. The passage was replaced immediately with five multiple-choice questions, and the participants were required to select one of three answers for each of the five questions before continuing.

Visual Word Recognition

Stimuli. Testing was achieved using the Reicher–Wheeler 2AFC task. One hundred twenty-eight matched pairs of four-letter words were selected as experimental stimuli, with a mean frequency of written occurrence of 114 per million (Francis & Kučera, 1982). The members of each word pair differed by just one letter (e.g., *wor<u>d</u>*, *wor<u>k</u>*), which occurred equally often at each of the four letter positions. The critical letters of each stimulus pair were matched in terms of both width and height (i.e., descenders and ascenders), so that each stimulus pair shared the same width, height, and spacing, to avoid response strategies based on local disparities between critical letters. Rearranging the noncritical letters in each word pair formed 128 pairs of matched nonword stimuli. The matched word and nonword stimuli used in the experiment are listed in the Appendix. An additional 64 word pairs and 64 nonword pairs were constructed to provide 128 practice stimuli at the beginning of each session. The fixation point was composed of a single pixel that was clearly visible to each participant.

Visual conditions. The words and nonwords were presented in black on a white background on the same gamma-corrected video monitor as that used to test contrast sensitivity and reading speed and in the same lowercase, 14-point font as that used to test reading speed. Background illumination of the monitor screen was approximately 46 cd/m^2, and the luminance of test stimuli was approximately 0.15 cd/m^2. Viewed from a distance of 57 cm, the average width of the words and nonwords subtended a horizontal visual angle of approximately 1º.

Image filtering. Image filtering was conducted using MATLAB Version 12.1 (MathWorks Ltd., Cambridge). Each stimulus was presented in the middle of the video monitor and was saved as a 256 × 256 pixel bitmapped (.bmp) file subtending horizontal and vertical visual angles of 11º × 11º. Each stimulus was then digitally filtered into eight different, 1-octave-wide bands of spatial frequencies with center (peak) frequencies of 1.1, 2.2, 3.5, 4.9, 6.7, 8.7, 11.1, and 13.7 cpd. This was achieved by pointwise multiplication in the frequency domain with fourth-order high- and low-pass Butterworth filters. The Butterworth filter is a mathematically tractable filter shape that avoids the problems of ringing associated with other filter shapes with a sharp cutoff (Fiorentini, Maffei, & Sandini, 1983; Russ, 1999; Schyns & Oliva, 1994, 1997, 1999). The high-pass and low-pass filter cutoff frequencies were 0.8–1.6, 1.65–3.3, 2.6–5.2, 3.7–7.4, 5.0–10.0, 6.5–13, 8.3–16.6, and 10.3–20.6 cpd. These bands of spatial frequencies were chosen so as to conform to previous psychophysical studies indicating selectivity to different spatial frequencies (e.g., Campbell & Robson, 1968) and to cover the range of spatial frequencies used to measure spatial frequency sensitivity in this study. They were also chosen on the basis of an earlier pilot study that showed that performance with these filtered stimuli encompassed a range of performance levels within threshold limits. In particular, identification of the words and nonwords was not possible with spatial frequency bands centered below 1.1 cpd, and so 1.1 cpd was the lowest band used. Post filtering, a constant zero frequency value was added to each filtered image to equate the background luminance of each image.

Design. The participants took part in four 50-min sessions, one on each of 4 days. Each session was divided into two sections (practice and experimental), with no obvious transition from one section to the next. Within each session, the stimuli were shown in pseudorandomly constructed cycles of 64 items, counterbalanced across stimulus type (word and nonword), spatial frequency, and critical letter position.

Procedure. At the start of each trial, a small fixation point appeared at the center of the screen. The participants were required to initiate each trial with a buttonpress. When the participants initiated a trial, the fixation point was replaced by the following display sequence: a 300-msec blank screen, the target stimulus, a 600-msec blank screen. Two unfiltered choices were then shown—the target and its matched alternative (e.g., *word*, *work*), one above the other in the center of the screen—and the participants had to decide which of these stimuli had been shown. To make their choice, the participants pressed one of two buttons to select either the upper or the lower alternative.

Throughout the practice and experimental sections, exposure durations were reassessed for each participant after each counterbalanced cycle of 64 trials. Exposure duration was increased (by 6 msec) if the number of correct responses in a cycle was below 40 (62.50%) and was decreased (by 6 msec) if the number of correct responses in a cycle was above 52 (81.25%). Within each cycle, all types of target were shown for the same exposure duration; when adjustments to exposure duration were made at the end of a cycle, the same adjustment was made for all types of targets. This adjustment procedure ensured that overall performance fell within the mid-range of the performance scale and that each condition (stimulus type × spatial frequency × critical letter position) was represented at the same exposure duration an equal number of times. Average exposure duration for stimulus presentations was 180 msec.

RESULTS

Reading Ability and Spatial Frequency Sensitivity

To identify good and poor readers, effective reading speed was calculated for each participant by multiplying the reading speed in words per minute (wpm) by the proportion of questions they answered correctly. Effective reading speed ranged from 124 (reading speed = 185 wpm, proportion of questions answered correctly = .67) to 356 (reading speed = 395 wpm, proportion of questions answered correctly = .90). For poor readers (identified as the bottom 25% of the participants in our sample), effective reading speeds ranged from 124 to 159 wpm (M = 142) and for good readers (identified as the top 25% of the participants in our sample), from 226 to 356 wpm (M = 256).

Visual acuities for all the participants ranged from −0.38 to −0.30 LogMAR ($M = -0.313$, $SD = 0.02$). No statistically reliable differences in visual acuity were found between good and poor readers [$t(18) = 0.21$, $p > .80$]. Nevertheless, good and poor readers did exhibit different patterns of spatial frequency sensitivity. The results of the spatial frequency sensitivity test for good and poor readers are shown in Figure 3. The sensitivity data were analyzed using an ANOVA with one between-subjects factor (reading ability) and one within-subjects factor (spatial frequency).[2] This analysis revealed main effects of reading ability [$F(1,18) = 4.57$, $p < .05$] and spatial frequency [$F(7,126) = 127.41$, $p < .001$] and an interaction between reading ability and spatial frequency [$F(7,126) = 12.26$, $p < .01$]. Newman–Keuls tests showed that good readers were more sensitive than poor readers to spatial frequencies of 2, 4, and 6 cpd (all ps $< .01$), but no differences in sensitivity were observed at any other frequencies.

For poor readers, sensitivity was lower for spatial frequencies of 0.5 and 4 cpd than for 1 and 2 cpd (ps $< .01$), lower for 6 cpd than for 0.5, 1, 2, and 4 cpd (ps $< .01$), lower for 8 and 10 cpd than for 0.5, 1, 2, 4, and 6 cpd (ps $<$ .01), and lower for 12 cpd than for 0.5, 1, 2, 4, 6, and 8 cpd (ps $< .05$). For good readers, sensitivity was lower for spatial frequencies of 1 and 4 cpd than for 2 cpd (ps $< .01$), lower for 0.5 and 6 cpd than for 1, 2, and 4 cpd (ps $< .01$), lower for 8 and 10 cpd than for 0.5, 1, 2, 4, and 6 cpd (ps $<$ .05), and lower for 12 cpd than for 0.5, 1, 2, 4, 6, and 8 cpd (ps $< .05$). No other comparisons were significant.

Reading Ability and Word and Nonword Perception

For poor readers, word and nonword exposure durations ranged from 151 to 204 msec ($M = 185$ msec, $SD =$ 17 msec). For good readers, stimulus exposure duration ranged from 146 to 216 msec ($M = 177$ msec, $SD =$ 23 msec). No statistically reliable differences in stimulus exposure duration were found between good and poor readers [$t(18) = 0.85$, $p > .40$].

Mean percentages of correct responses to word and nonword stimuli for good and poor readers are shown in Figure 4. These data were submitted to an ANOVA with one between-subjects factor (reading ability) and two within-subjects factors (stimulus type and spatial frequency). The analysis revealed main effects of stimulus type [$F(1,18) = 53.13$, $p < .001$] and spatial frequency [$F(7,126) = 118.82$, $p < .001$] but no main effect of reading ability or any interactions.

Newman–Keuls comparisons showed that response accuracy for stimuli with a center spatial frequency of 1.1 cpd was essentially at chance and lower than that for all other frequencies (ps $< .01$). In addition, accuracy was lower for center frequencies of 2.2 and 13.7 cpd than for 3.5, 4.9, 6.7, 8.7, and 11.1 cpd (ps $< .01$), lower for 3.5 and 11.1 cpd than for 4.9, 6.7, and 8.7 cpd (ps $< .01$), and lower for 8.7 cpd than for 4.9 and 6.7 cpd (ps $< .01$). No other comparisons were significant.

Although performance at 1.1 cpd was essentially at chance for good and poor readers and so contributed little to the overall word–nonword effect that was observed, a slight (1%) advantage for nonwords over words did occur for poor (but not good) readers at this spatial frequency. To ensure that the absence of a significant difference between the pattern of word–nonword effects produced by good and poor readers was not merely the result of using an omnibus analysis, the pattern of performance produced by good and poor readers was examined further by two subsidiary ANOVAs, one for each reading ability. The results confirmed the findings of the omnibus analysis. Each subsidiary ANOVA (with factors of stimulus type and spatial frequency) revealed main effects of stimulus type [for good readers, $F(1,9) = 29.86$, $p < .001$; for poor readers, $F(1,9) = 23.42$, $p < .001$] and spatial frequency [for good readers, $F(7,63) = 62.50$, $p < .001$; for poor readers, $F(7,63) = 68.19$, $p < .001$] and no interaction. Newman–Keuls comparisons revealed the same pattern of performance across spatial frequency conditions as that in the omnibus analysis, for both reading abilities.

DISCUSSION

One aim of the present study was to determine whether differences in spatial frequency sensitivity found previously between dyslexic and nondyslexic controls extend to the normal adult population. A second aim was to examine directly the role of different spatial frequencies in visual word perception by examining the perceptibility of frequency-filtered words and nonwords, using the Reicher–Wheeler task to provide a stringent assessment of perception without nonperceptual influences. Moreover, by comparing performance with filtered words and nonwords between good and poor readers, our aim was to assess the ability of good and poor readers to use the spatial frequency information available in words (and nonwords).

Reading Ability and Spatial Frequency Sensitivity

Primary evidence for frequency-selective pathways in vision has come from studies with gratings (e.g., Blakemore & Campbell, 1969; Campbell & Robson, 1968), and the present findings reveal that normal adults of good and

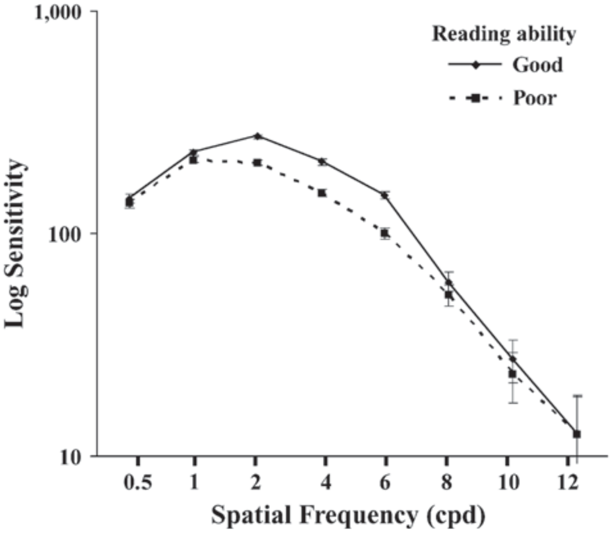

Figure 3. Contrast sensitivity (1/contrast threshold) for good and poor readers.

poor reading abilities have different patterns of sensitivity for detection of sinusoidal gratings. In particular, despite having normal visual acuity, poor readers showed reduced sensitivity to spatial frequencies of 2, 4, and 6 cpd, relative to good readers. This finding resonates with those found previously between dyslexic and nondyslexic controls (Borsting et al., 1996; Cornelissen, 1993; Demb et al., 1998; Evans et al., 1993, 1996; Lovegrove et al., 1980; Lovegrove et al., 1982, Experiment 2; Martin & Lovegrove, 1984, 1988), indicating that differences in sensitivity found previously between dyslexic and nondyslexic controls can be extended to the normal adult population.[3]

One account of the spatial frequency sensitivity differences found previously between dyslexic and nondyslexic controls is that dyslexic individuals suffer from a "magnocellular deficit" (Stein & Walsh, 1997). This account is based on psychophysical, physiological, and anatomical evidence indicating two primary sensory-processing channels in the mammalian visual system, commonly known as the *magnocellular* and *parvocellular* systems. Essentially, the magnocellular system mediates low spatial and high temporal frequency information, whereas high spatial and low temporal frequency information is mediated by the parvocellular system. The magnocellular deficit theory postulates that dyslexic individuals suffer from impaired temporal processing of briefly fixated words. In particular, the magnocellular system is thought to play a special role in reading by suppressing activation elicited during one fixation from lingering into that elicited during the next fixation (Stein & Walsh, 1997). Other investigators (Allen & Emerson, 1991; Allen & Madden, 1990; Allen, Wallace, & Weber, 1995; Healy, Oliver, & McNamara, 1987; Rudnicky & Kolers, 1984) have also developed accounts of visual word recognition that incorporate a role for coarse and fine scale information. For example, Allen et al. (1995) set out the parallel input serial analysis (PISA) model of visual word recognition, in which whole word and letter level codes are processed independently and in parallel. Indeed, the general description of the process of word recognition in this model can be mapped onto the magnocellular and parvocellular pathways of the visual system (Allen et al., 1995).

However, the present study suggests that (nondyslexic) adults of poor reading ability have deficits in sensitivity to spatial frequencies only in the midfrequency range, between 2 and 6 cpd, whereas the spatial frequencies processed exclusively by the magnocellular system are estimated to be below 1.5 cpd (Skottun, 2000), and spatial frequencies above 1.5 cpd may be processed by the parvocellular system. Consequently, although a magnocellular deficit may underlie the reading ability of some dyslexic individuals, the present study indicates no differences in sensitivity to spatial frequencies below 1.5 cpd between good and poor readers of "normal" reading ability. Thus, it is unclear whether differences in magnocellular functioning also underlie differences in the reading ability of normal adults. This does not rule out accounts of visual word recognition that posit an important role for the magnocellular system in reading and word perception but suggests that accounts that posit a dichotomy of the spatial frequencies contained in words into those processed by either the magnocellular or the parvocellular system may be too simple.

Reading Ability and Word and Nonword Perception

The identification of band-pass filtered stimuli by good and poor readers showed that although performance was best for both reading abilities for stimuli with center fre-

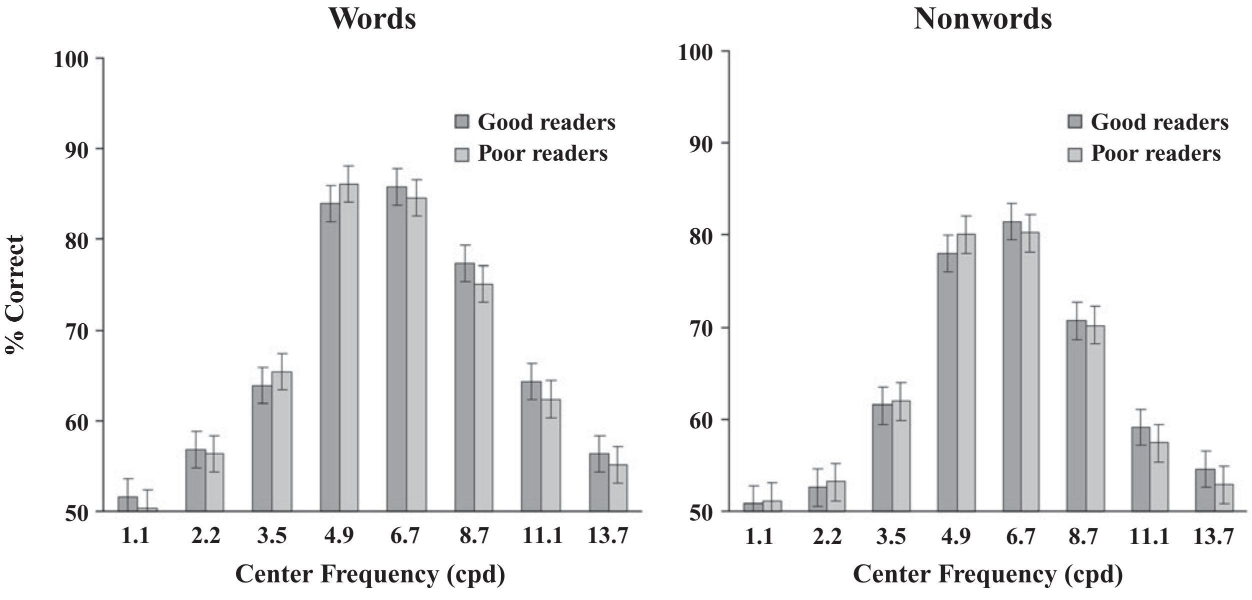

Figure 4. Mean percentages of correct responses (% correct) for good and poor readers at each center frequency for words and nonwords.

quencies of 4.9 and 6.7 cpd, identification accuracy was above chance for stimuli at all but 1.1 cpd. This suggests that spatial frequencies in the midrange specify the identity of words and nonwords best of all but that useful information for identifying words and nonwords exists over a range of spatial frequencies (specifically, in the present study, in 1-octave-wide bands of spatial frequencies with center frequencies of 2.2, 3.5, 4.9, 6.7, 8.7, 11.1, and 13.7 cpd). Moreover, at each of these frequencies, identification accuracy was higher for words than for nonwords, indicating that information at these spatial frequencies produced different patterns of activation for word and nonword targets (e.g., Grainger & Jacobs, 1994, 1996; Jacobs & Grainger, 1994; Johnston & McClelland, 1980; Jordan et al., 2000; Jordan et al., 2003a, 2003b; Jordan, Redwood, & Patching, 2003; McClelland & Rumelhart, 1981, 1988; Paap et al., 1982; see also Carr & Pollatsek, 1985). The precise nature and extent of these differences in activation produced by the filtered images of words and nonwords used in this study remains to be determined. However, the evidence so far is that good and poor readers can use information at each spatial scale more effectively for perception of words than for perception of other types of letter strings.

These findings extend a growing body of research that suggests an important role for coarse scale (low-frequency) and fine scale (high-frequency) visual information in reading (Allen & Madden, 1990; Boden & Giaschi, 2000; Dakin & Morgan, 1999; Jordan, 1990, 1995; Jordan & Bevan, 1996; Jordan & de Bruijn, 1993; Leat & Munger, 1994; Legge, Pelli, et al., 1985). However, the present findings go further by showing that a range of narrow bands of spatial frequencies, from coarse to medium, to fine scale, can independently activate processes of word perception. On this basis, word perception is mediated not by a single division of the spatial frequencies contained in words into those processed by either the magnocellular or the parvocellular system, but by finer grained divisions of spatial frequencies into various narrow bands specifying different aspects of words, such as letter features (in our study, which used four-letter words subtending approximately 1º of horizontal visual angle, 8–16 cpd), letters (in our study, 4–8 cpd), subword letter groups (in our study, 2–4 cpd), and the overall spatial extent of four-letter words (in our study, 1–2 cpd).[4] In this respect, models of visual word recognition (e.g., PISA) would do well to incorporate a role for more fine grained analyses of the spatial frequencies contained in words when accounting for visual word perception. Indeed, words vary in physical extent and can be perceived accurately from a variety of viewing distances and, therefore, spatial scales. Consequently, various narrow spatial frequency bands may be used to encode different aspects of words, depending on their physical extent and the distance at which they are viewed.

The findings of the present study provide no indication that the magnocellular system alone (processing spatial frequencies below 1.5 cpd; Skottun, 2000) can support word perception. Perception of words and nonwords with a center frequency of 1.1 cpd was essentially at chance. Moreover, no differences were found between good and poor readers in perception of words and nonwords at that spatial scale (see Figure 4), and words containing higher spatial frequencies may be processed by the parvocellular system (Skottun, 2000). Consequently, although the magnocellular system may play an important role in word perception when a broad range of spatial frequency information is processed together (Chase, 1996), the evidence so far suggests that good readers are no more able than poor readers to use the low spatial frequency information processed by the magnocellular system for word perception.

Finally, it should be noted that although good and poor readers showed different patterns of sensitivity in detection of sinusoidal gratings, good and poor readers showed no differences in their perceptibility of filtered word and nonword stimuli. Indeed, good and poor readers showed similar inverted U-shaped functions for words and nonwords across the range of center frequencies used, and both groups showed substantial and wide-ranging word–nonword effects. Moreover, good and poor readers' sensitivity to sinusoidal gratings was greatest for spatial frequencies of 2 and 1 cpd, respectively, but perception of words (and nonwords) by good and poor readers was most accurate for stimuli with center frequencies of 4.9 and 6.7 cpd. Furthermore, although sensitivity to spatial frequencies from 2 to 6 cpd was lower for poor readers than for good readers, perception of words and nonwords with a center frequency of 3.5 cpd (which contained only those spatial frequencies within this reduced sensitivity range) was equivalent for good and poor readers. This suggests that the precise link between patterns of sensitivity to sinusoidal gratings and word perception is far from straightforward, and further work is required to develop assessments of the role of spatial frequency perception in reading ability. Indeed, the evidence so far indicates that a broad range of spatial frequencies may be used in word recognition and may be used with equal effect by good and poor readers (see Figure 4). Consequently, a more appropriate way of assessing an individual's sensitivity to spatial frequencies when reading would be to use filtered word and nonword stimuli (of the type used in the present study) and to test recognition ability by using the stringent Reicher–Wheeler task, which overcomes problems with guesswork and strategy. Indeed, individual differences in sensitivity to certain spatial frequencies within words may affect the weighting attached to different spatial frequencies in word recognition, and people with different patterns of sensitivity to the spatial frequency content of words may rely on different spatial frequencies for recognizing words. However, these differences may be revealed only when word recognition is tested explicitly, under appropriate testing conditions.

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NOTES

1. We report spatial frequencies in terms of retinal coordinates (i.e., cycles per degree), although the average width of the word and nonword stimuli subtended 1º of visual angle, equating cycles per degree and cycles per word in our study. Most psychophysical studies of spatial frequency bands and, in particular, studies of the spatial contrast sensitivity function (e.g., Blakemore & Campbell, 1969; Campbell & Robson, 1968) have focused on retinal spatial frequency—that is, spatial frequencies defined in terms of retinal coordinates.

2. The data reported in this article were also analyzed following arcsine transformation, as recommended by Winer (1971, p. 400). The patterns of performance revealed by analysis of the raw data remained unchanged by arcsine transformation. Therefore, for brevity, only the analyses of the raw data are reported.

3. Previous studies with dyslexic individuals tested performance with a small range of spatial frequencies (typically, no more than four) and showed a drop in sensitivity to all spatial frequencies tested, which may have reflected merely an overall lack of attention to the task (Stuart, McAnally, & Castles, 2001) or, indeed, overall differences in intellectual ability. In contrast, the present study tested sensitivity over a wider range of spatial frequencies (eight, from 0.5 to 12 cpd) and revealed no overall deficits for poor readers but, instead, deficits only at specific spatial frequencies. Consequently, it seems unlikely that problems concerning overall differences in attention to the task or in intellectual ability between good and poor readers can account for the selective reduction in spatial frequency sensitivity observed in the present study.

4. Precisely how sensitivity to retinal spatial frequency relates to object spatial frequency in word perception has yet to be determined. The spatial frequency information in words can be described in terms of retinal frequencies (cycles per degree) that are dependent on viewing distance, or in terms of object frequencies (cycles per word) that are defined in terms of some dimension of the object that they describe and are independent of viewing distance. In the present case, and as was noted earlier, these two measures are equivalent in our study.

APPENDIX

dear	bear	dera	bera	tags	taps	atgs	atps	read	road	aerd	aord
dent	bent	dnte	bnte	rags	raps	srga	srpa	duck	deck	kucd	kecd
dips	kips	dsip	ksip	tube	tuba	tbue	tbua	went	want	tewn	tawn
drew	brew	dwer	bwer	halt	half	alht	alhf	cast	cost	tasc	tosc
sack	sock	kasc	kosc	trap	tray	atrp	atry	case	care	aesc	aerc
colt	cult	tocl	tucl	bard	bark	abrd	abrk	rent	rest	rtne	rtse
legs	logs	selg	solg	omit	emit	oimt	eimt	lard	land	adrl	adnl
bets	bats	tesb	tasb	pain	gain	pnai	gnai	slob	slab	lbos	lbas
rise	rice	irse	irce	pear	year	prae	yrae	bash	bask	absh	absk
past	pact	atsp	atcp	take	fake	tkae	fkae	gush	gust	usgh	usgt
cone	cove	ecno	ecvo	ages	apes	egsa	epsa	card	carf	acrd	acrf
live	line	ievl	ienl	post	pest	tosp	tesp	stag	stay	tasg	tasy
warp	wary	rawp	rawy	pert	port	rept	ropt	bogs	dogs	bgso	dgso
clap	clay	aclp	acly	luck	lack	cukl	cakl	jogs	togs	jsgo	tsgo
snag	snap	nasg	nasp	blew	blow	bwel	bwol	wink	mink	wnki	mnki
curb	curd	urcb	urcd	crow	crew	rwoc	rwec	rink	sink	rkni	skni
tour	four	toru	foru	flow	flew	lwof	lwef	acts	arts	atcs	atrs
bold	fold	blod	flod	tack	task	atck	atsk	worm	warm	mowr	mawr
grey	prey	gyar	pyar	flag	flap	alfg	alfp	rote	rate	eotr	eatr
hand	band	hdna	bdna	hero	here	erho	erhe	tune	tone	eunt	eont
held	hold	lehd	lohd	lust	lush	uslt	uslh	ruse	rune	eusr	eunr
bust	best	subt	sebt	limo	lime	ilmo	ilme	bake	bade	abke	abde
bath	both	tahb	tohb	tear	fear	taer	faer	fare	face	afze	afce
oven	oxen	evno	exno	pour	your	poru	yoru	slat	slot	ltas	ltos
robe	rode	erbo	erdo	rung	sung	rngu	sngu	rush	rust	ursh	urst
love	lone	olve	olne	beam	team	bmae	tmae	pans	pane	apns	apne
bags	bays	asgb	asyb	shop	stop	phso	ptso	this	thin	htis	htin
fast	fact	ftsa	ftca	left	loft	fetl	fotl	lain	lair	ailn	ailr
herb	herd	ehrb	ehrd	send	sand	nesd	nasd	vice	nice	vcie	ncie
flog	flop	folg	folp	most	must	tosm	tusm	tong	dong	tnog	dnog
flex	flea	lfex	lfea	mask	mark	mksa	mkra	rant	cant	rnta	cnta
waif	wait	iwaf	iwat	neat	next	tnae	tnxe	fate	date	faet	daet
heat	beat	htae	btae	gaze	gave	egza	egva	romp	ramp	rmpo	rmpa
hive	dive	hiev	diev	doze	dove	odze	odve	torn	turn	nort	nurt
oars	ears	orsa	ersa	knob	knot	oknb	oknt	sang	song	gasn	gosn
oats	eats	otsa	etsa	stew	stem	estw	estm	role	rule	eorl	eurl
lest	last	tesl	tasl	bore	born	obre	obrn	pose	pore	opse	opre
loaf	leaf	aofl	aefl	barn	bare	abrn	abre	race	rave	aecr	aevr
damp	dump	mapd	mupd	dame	fame	dmea	fmea	grab	grub	rgab	rgub
rock	rack	kocr	kacr	note	vote	noet	voet	ploy	play	lyop	lyap
mare	maze	amre	amze	brag	drag	bgar	dgar	pine	pins	inpe	inps
bead	bend	bdae	bdne	deal	heal	dael	hael	tale	talc	atle	atlc
fain	fair	aifn	aifr	welk	weld	lwek	lwed				

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