Sensitivity to dynamic auditory and visual stimuli predicts nonword reading ability in both dyslexic and normal readers

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Background: Developmental dyslexia is a specific disorder of reading and spelling that affects 3–9% of school-age children and adults. Contrary to the view that it results solely from deficits in processes specific to linguistic analysis, current research has shown that deficits in more basic auditory or visual skills may contribute to the reading difficulties of dyslexic individuals. These might also have a crucial role in the development of normal reading skills. Evidence for visual deficits in dyslexia is usually found only with dynamic and not static stimuli, implicating the magnocellular pathway or dorsal visual stream as the cellular locus responsible. Studies of such a dissociation between the processing of dynamic and static auditory stimuli have not been reported previously.

Results: We show that dyslexic individuals are less sensitive both to particular rates of auditory frequency modulation (2 Hz and 40 Hz but not 240 Hz) and to dynamic visual-motion stimuli. There were high correlations, for both dyslexic and normal readers, between their sensitivity to the dynamic auditory and visual stimuli. Nonword reading, a measure of phonological awareness believed crucial to reading development, was also found to be related to these sensory measures.

Conclusions: These results further implicate neuronal mechanisms that are specialised for detecting stimulus timing and change as being dysfunctional in many dyslexic individuals. The dissociation observed in the performance of dyslexic individuals on different auditory tasks suggests a sub-modality division similar to that already described in the visual system. These dynamic tests may provide a non-linguistic means of identifying children at risk of reading failure.

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Background

Developmental dyslexia or specific reading disability affects between 3% and 9% of school children [1] and is typically diagnosed by a large deviation of reading and spelling achievement from that which would be expected from age-based and/or IQ-based norms [2]. The most popular theory is that these reading and spelling problems result exclusively from impaired phonological processes that are specific for linguistic analysis [3–5]. From this point of view, dyslexic individuals are less able to decode and transform linguistic input into the phonological code that relates letter units (graphemes) to speech sounds (phonemes) [6]. It is now clear that many individuals with developmental dyslexia also have sensory deficits, however, especially for the detection of rapidly changing stimuli ([7,8]; see also [9] for review). Between-group differences are rarely found with static stimuli unless they have brief durations or short interstimulus intervals (ISIs), that is, when processing time is restricted [9]. In auditory detection studies, subjects with dyslexia are often found to be less sensitive than control subjects at distinguishing both linguistic stimuli (for example, synthetic stop consonants or steady state vowels) and non-linguistic stimuli (for example, pure tones) that either change rapidly in time or have short durations [10,11]. It has been suggested that such an auditory dysfunction could underlie the pervasive difficulties that dyslexic readers have with phonological decoding because many phoneme discriminations, such as distinguishing ‘ba’ from ‘da’, require the detection of rapid and transient formant frequency changes within a brief temporal window of the order of 40 milliseconds [10,12–14].

The difficulties that dyslexic subjects have with phonological decoding are well demonstrated in tasks of nonword reading [15]. Nonwords (for example, ‘tegwop’) can be correctly read only by applying the relevant grapheme–phoneme correspondence rules. Such tasks can discriminate good readers from poor readers at early ages [16] and also in adulthood [17]. Tallal [10] has proposed that these phonological difficulties result from an inability to discriminate the temporal order of brief linguistic events that occur over the time frame of milliseconds. It has also been shown that many dyslexic individuals have deficits in detecting dynamic visual stimuli such as coherent motion and flicker [8,18,19]. Good visual temporal processing is likely to be necessary for the accurate encoding of letter position that is required for accurate reading [20]. Talcott *et al.* [21] have also recently shown that nonword reading correlates strongly with measures of visual magnocellular function, suggesting that visual temporal perception has an important role in reading development. Impaired detection of visual dynamic stimuli is usually found in the presence of normal detection thresholds for non-dynamic stimuli [9]. This dissociation has led to the hypothesis that visual sensory deficits of dyslexic individuals are restricted to stimuli that selectively stimulate the magnocellular but not the parvocellular retinocortical stream [22]. Nevertheless, it should be noted that other types of neurological dysfunction have been suggested to be the bases of the temporal processing deficits often observed in dyslexia (for example, see [23,24]).

Studdert-Kennedy and Mody [6] have pointed out that the definition of a temporal processing deficit as suggested by Tallal (for example, see [10]) and Farmer and Klein [9] makes it important to appreciate the distinction between ‘rate of perception’ and ‘perception of rate’. Tallal, and Farmer and Klein, define temporal processing as the processing of stimuli which are presented rapidly, or which have spectral changes over a very short time (tens of milliseconds), and hence Studdert-Kennedy and Mody suggest that this measures rate of perception. Studdert-Kennedy and Mody proposed that stimulus processing should be considered temporal only when the defining features of the stimuli are changing in time, and that stimuli should not be defined as being temporal solely by virtue of being briefly presented (for example, short durations or ISIs). In the studies reported here, we are concerned primarily with dynamic stimulus detection (that is, perception of rate). Therefore, we have used long-duration stimuli that require the perception of a dimension changing in time. Such measures might provide a more direct test of temporal processing ability that can also be plausibly linked to underlying neural sensitivity. Accurate detection of dynamic stimuli in the visual domain is likely to depend upon dorsal stream structures with a predominance of magnocellular input [25–27].

No studies to date have considered both dynamic auditory and visual temporal perception in the same subjects and related phonological skills to these sensory abilities. If concurrent, dissociated deficits in dynamic auditory and visual processing were found in individuals with developmental dyslexia, however, this would provide evidence for a subdivision of the visual and auditory systems that is responsible for encoding information about stimulus timing and change [12,22]. In this study, therefore, we have measured the sensitivity of dyslexic and control subjects to dynamic auditory and visual stimuli. We show how these correlate with each other and that they predict phonological ability as assessed by nonword reading.

Results and discussion

Detection of frequency modulation

Impaired processing of frequency modulation (FM) in sound has been demonstrated in some neurological conditions associated with impairments of receptive language [28–30] and in dyslexic adults [11]. We have measured detection thresholds for FM of a tone at three different rates: 2 Hz, at which all subjects could track the changes in the pitch of the sound; 40 Hz (the highest modulation frequency necessary for accurate perception of speech reconstructed with a phase vocoder [31]), at which frequency changes are perceived as ‘roughness’ [32]; and 240 Hz, at which subjects detect the presence of a tone at the pitch of the modulating frequency [32] (a perceived component not present in the spectrum), implying a mechanism that is probably dependent upon nonlinearly generated cues [33]. The spectra of the tones modulated at 2 Hz and 40 Hz are both encompassed by a single auditory critical bandwidth, whereas the spectrum of the tone modulated at 240 Hz extends beyond a single critical band. The perception of these modulations reflects different FM processing mechanisms because, at 2 Hz and 40 Hz, the percept depends upon temporal aspects of the stimulus whereas, at 240 Hz, it depends upon spectral cues. If dyslexic individuals have impaired temporal processing of FM, we predict a dissociation between their performance at slow (2 Hz and 40 Hz) and rapid (240 Hz) rates of FM.

Auditory thresholds were compared by a 2 (group) × 3 (FM condition) analysis of variance (ANOVA). Post hoc analysis of interaction terms was performed using t tests (with degrees of freedom corrected for variance inhomogeneity when necessary) with p adjusted to minimise the type I error rate. For the FM thresholds, both the main effects of group, dyslexic versus control subjects ($F(1, 105) = 13.393$, $p \leq 0.001$), and FM condition ($F(2, 105) = 220.74$, $p \leq 0.001$) were significant as was the group by FM condition interaction ($F(2, 105) = 12.881, p \leq 0.001$).

Mean FM detection thresholds for dyslexic and control subjects are shown in Figure 1. FM detection thresholds were significantly higher in the dyslexic group than the control group for both 2 Hz and 40 Hz FM (2 Hz: $t(28.61) = 3.663$, $p \leq 0.001$, two-tailed t test; 40 Hz: $t(41) = 2.288$, $p = 0.027$, two-tailed t test), whereas detection thresholds for 240 Hz FM were not significantly different between the groups ($t(41) = 0.926$, $p = 0.360$, two-tailed t test). FM detection deficits in developmental dyslexia appear to be specific to slower modulations in frequency. This suggests that dyslexic subjects have difficulties detecting the temporal modulation of the stimuli rather than the tonal cues which are perceived at higher modulation rates.

The thresholds of subjects for 2 Hz and 40 Hz FM correlated with each other ($r = 0.419$, $p \leq 0.005$), but neither correlated with 240 Hz FM performance (2 Hz and 240 Hz FM, $r = 0.191$, $p = 0.221$; 40 Hz and 240 Hz FM, $r = 0.040$, $p = 0.799$). This confirms the findings by Zwicker [32] and Green [33] that different auditory mechanisms are responsible for the detection of low-frequency and high-frequency modulation.

Detection of coherent motion

We used random dot kinematograms (RDK) similar to those employed by Newsome and Pare [34] to measure putative visual magnocellular pathway sensitivity. Cornelissen and colleagues [8] had found previously that detection thresholds for RDK motion were higher in dyslexic adults and children than in chronological-age-matched controls. Eden *et al.* [35] showed, using functional magnetic resonance imaging, that dyslexic individuals also lacked significant activation of a cortical area (V5 or MT) that is normally sensitive to visual motion when presented with RDK stimuli.

Figure 2 shows the detection thresholds of control and dyslexic subjects for coherent motion in RDKs. Consistent with earlier work [8,21], the dyslexic subjects were found to be significantly less sensitive than the control subjects ($t(23.065) = 2.343$, $p = 0.028$, two-tailed t test), that is, they needed a greater proportion of coherently moving dots to detect either leftward or rightward motion.

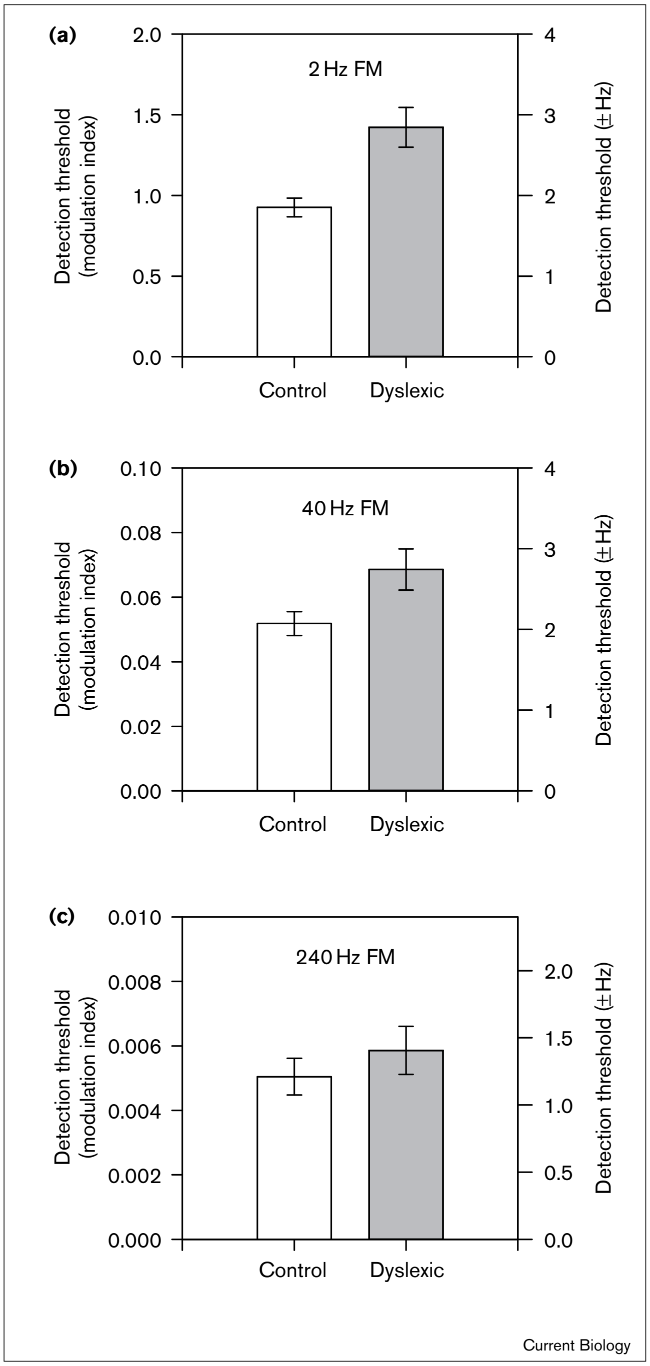
Correlational analyses of sensory thresholds

As shown in Figure 3, thresholds for 2 Hz FM and coherent motion detection correlated strongly ($r = 0.535$, $p \leq 0.001$). These correlations show that high sensitivity to 2 Hz FM (that is, lower thresholds) was associated with increased sensitivity to coherent motion. Thresholds for 40 Hz FM also correlated significantly with motion coherence thresholds, though less strongly ($r = 0.374$, $p = 0.027$), whereas thresholds for 240 Hz FM and motion detection were unrelated ($r = 0.048$, $p = 0.785$).

Correlational analyses of reading and sensory thresholds

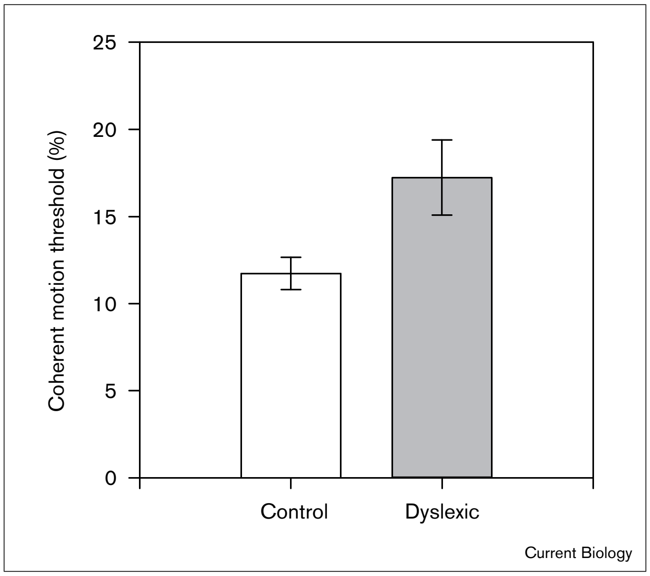
The Castles and Coltheart [36] nonword reading task was used as a measure of phonological performance. Each subject's accuracy (number of incorrect responses) and overall time taken to read the words aloud was recorded. Both accuracy and nonword reading time correlated significantly with FM detection performance at 2 Hz (accuracy: $r = 0.526$, $p \leq 0.01$; time: $r = 0.467$, $p \leq 0.01$) and 40 Hz (accuracy: $r = 0.453$, $p \leq 0.01$; time: $r = 0.327$, $p \leq 0.05$), but not at 240 Hz (accuracy: $r = -0.030$, $p > 0.05$; time: $r = 0.139$, $p > 0.05$). These nonword reading measures were similarly related to the subject's thresholds for coherent

Figure 1



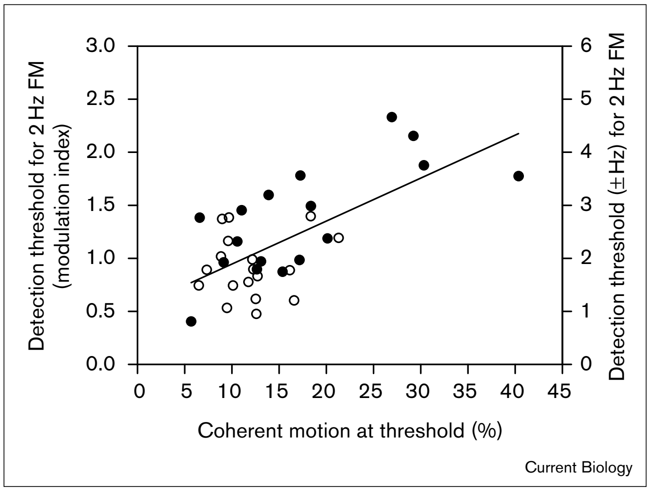
Thresholds for detecting FM at three different rates, for control and dyslexic groups: **(a)** 2 Hz FM of a 500 Hz tone; **(b)** 40 Hz FM of a 500 Hz tone; and **(c)** 240 Hz FM of a 1 kHz tone. Error bars are ± 1 standard error. The left vertical axis shows the detection threshold in terms of the modulation index, which is defined as the depth of modulation (in ± Hz) divided by the rate of modulation. The right vertical axis shows detection threshold in ± Hz.

Figure 2



Thresholds for detecting coherent motion in a RDK, for control and dyslexic subjects. Error bars are ± 1 standard error. Motion-detection thresholds are defined as the average percentage of coherently moving dots required for the subject to discriminate leftward from rightward motion. See text for details.

Figure 3



Thresholds for detecting 2 Hz FM of a 500 Hz tone, plotted against thresholds for coherent-motion detection, for 18 control and 17 dyslexic subjects. Empty circles, control subjects; filled circles, dyslexic subjects. The left and right vertical axes are as described in the legend to Figure 1.

motion detection (accuracy: $r = 0.347$, $p \leq 0.05$; time: $r = 0.541, p \leq 0.01$).

In timed tasks, however, individual subjects often traded reading accuracy for time, or vice versa, as suggested by the non-unity correlation coefficient between the nonword reading measures, accuracy and time ($r = 0.675$, $p < 0.01$). Therefore, a more comprehensive measure of nonword reading performance can be obtained by combining these two important variables. The accuracy and time scores were scaled equally and combined using linear principal components analysis (PCA) to form a single unitary measure of nonword reading performance (error time). This reduced measure accounted for 93.6% of the variance of the two individual measures.

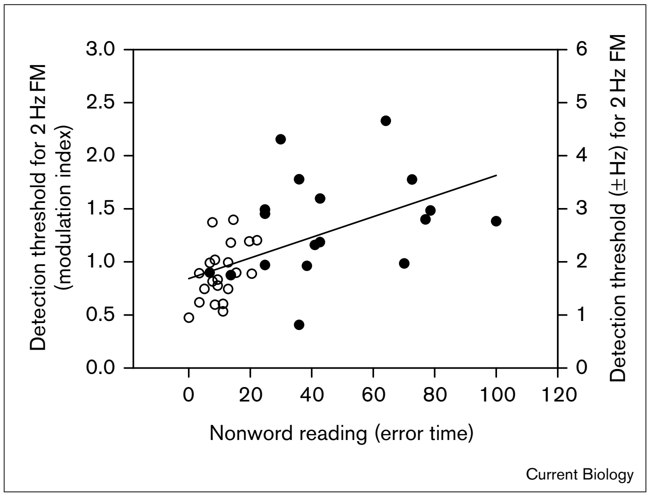
Figure 4 shows the correlation between nonword error time and detection thresholds for 2 Hz FM. Nonword error time correlated highly with lower frequency FM (2 Hz and 40 Hz) but not with higher frequency FM (240 Hz) performance. The correlations between nonword error times were $r = 0.603$, $p \leq 0.01$ for 2 Hz FM, and $r = 0.408$, $p \leq 0.05$ for 40 Hz FM, but only $r = 0.082$, $p > 0.05$ for 240 Hz FM. Thresholds for visual coherent motion also correlated with error time ($r = 0.406, p \leq 0.05$), although less strongly than for 2 Hz FM. Thus, up to 36% of the variance in nonword reading performance (error time) could be accounted for by knowing their thresholds on our perceptual tasks.

Conclusions

The main conclusion of this study is that dyslexic subjects are less sensitive than control subjects at detecting both visual coherent motion in RDK stimuli and low rates of auditory FM (2 Hz and 40 Hz), whereas their thresholds for 240 Hz auditory FM are not significantly different. Furthermore, for both dyslexic and normal readers, low frequency FM sensitivity and visual-motion sensitivity correlated highly. Finally, both our auditory and visual measures of temporal perception predicted significant proportions of the variance in phonological skills of both dyslexic and control subjects, as assessed by nonword reading.

Timing of stimuli in the visual system is dependent upon a system of large neurons comprising the magnocellular retinocortical stream, one of the two main parallel visual pathways [25,27]. High temporal sensitivity is a characteristic property of the receptive fields of these magnocells [25,27]. They have large cell bodies, thick myelinated axons and, consequently, high conduction velocities that provide an efficient substrate for encoding information about stimulus timing and change. Lesions to cortical and sub-cortical visual areas which receive predominant magnocellular input therefore cause selective deficits in the detection of time-varying stimuli, such as motion and flicker, without impairing non-temporal visual functions, such as colour and form discrimination [26,34,37]. There is now considerable evidence that dyslexic individuals have impairment of the visual magnocellular system (see [22] for review), and our demonstration here that dyslexic individuals have lower sensitivity to visual motion provides further support for this idea.

Figure 4



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Thresholds for detecting 2 Hz FM of a 500 Hz tone, plotted against a combined measure of nonword reading and reading time (error time) for 21 control and 18 dyslexic subjects. Empty circles, control subjects; filled circles, dyslexic subjects. The left and right vertical axes are as described in the legend to Figure 1.

The dissociation between FM performance at low (2 Hz and 40 Hz) and high (240 Hz) frequencies suggests that dyslexic readers have an auditory deficit that selectively impairs temporal perception and that is similar to their visual magnocellular deficit. Their detection thresholds for the 240 Hz FM stimulus were not different from those of control subjects, probably because 240 Hz FM sensitivity depends on detecting nonlinearly generated tonal cues rather than tracking changes in frequency over time. Also the fact that their 240 Hz FM performance was normal refutes the idea that dyslexic readers are generally poorer than control subjects at all psychophysical tests.

Galaburda and colleagues [38,39] have provided neuropathological evidence that dyslexic individuals have a cellular impairment. They demonstrated abnormalities specific to magnocell cell types of both the auditory and visual relay nuclei of the thalamus (medial geniculate and lateral geniculate nuclei, respectively). Our psychophysical findings that dyslexic individuals are less sensitive to both visual and auditory dynamic stimuli provide further support for their having impaired development of neuronal mechanisms responsible for encoding timing information [10,12,22].

Tallal has argued that a consequence of an auditory temporal-perception deficit might be a difficulty in discriminating between the speech sounds that characterise different phonemes [10,12]. However, Nicolson and Fawcett [24] propose that this problem may result from an impairment at the decision stage rather than at the level of perceptual encoding. In our experiments, the stimuli were of long duration and response times of subjects were not restricted. Thus, our demonstration that 2 Hz and 40 Hz FM sensitivity accounted for a significant proportion of the nonword reading performance of both control and dyslexic subjects supports the notion that perceptual encoding is impaired in dyslexic individuals. This suggests an important role for basic auditory temporal processing in coding the information required to discriminate phonemes in speech. Such a causal relationship has yet to be proven. Despite the evidence for the importance of linguistic-processing deficits in the aetiology of dyslexia, our results show that dyslexic subjects differ reliably from control subjects on performance of certain auditory and visual tasks, specifically ones that measure temporal perception. In addition, nonword reading ability correlates with these sensory measures. Thus, our tests might provide a non-linguistic means to identify children at risk of dyslexic problems before their reading begins to fail.

Materials and methods

Subjects

All of our methods were performed in accordance with the guidelines set forth in the Declaration of Helsinki and had approval from the local ethics committee. The subjects were 21 adults with developmental dyslexia (mean age = 30.4; SD = 9.4) and 23 similarly aged controls (mean age = 30.5, SD = 10.6); 15 of the dyslexic individuals and 10 of the controls were male. All were native English speakers. All of the dyslexic subjects had been previously diagnosed by educational or clinical psychologists on the basis of reading and spelling performance that was significantly lower than was expected from their measured intelligence on the Wechsler Adult Intelligence Scales (WAIS-R) [40]. We also re-tested their reading and spelling with the Wide Range Achievement Test (WRAT) [41]. At the time of testing, each dyslexic subject had a reading and spelling deficit of at least 1.0 standard deviation (15 standard score units) from their expected ability. None of the controls had such a discrepancy. Each subject also completed a nonword reading battery [36] as well as the Digit Span and Digit Symbol subtests of the WAIS-R. Most of the subjects ($n = 15$ for each group) also completed the Similarities and Picture Arrangement subtests. Performance on these measures was not significantly different between the groups. The descriptive statistics for the dyslexic and control subjects are shown in Table 1.

FM detection

Auditory stimuli were generated using Tucker Davis Technologies System II equipment, and were presented to the subjects through headphones (Sennheiser HD 40) in a quiet room. Before collection of data, subjects were given a short period of practice (about five suprathreshold trials) to familiarise them with the stimuli. Pure tone detection thresholds were also measured on all subjects to ensure that they had no hearing loss at the frequencies used in the study.

All auditory psychophysical measurements were performed using a two-alternative forced-choice paradigm. Subjects were presented with pairs of sounds: one was a pure tone, the other an FM tone (the target tone). They were required to report verbally which tone, first or second, was the target. Ten trials were performed at each of six depths of FM, chosen to span the threshold in equal intervals. For each trial the modulation depth and order of presentation of the tones was randomly assigned. A psychometric function was constructed from the data, relating the number of trials in which the subject correctly identified the target to the frequency modulation depth. The psychometric function

Table 1

Descriptive statistics for control and dyslexic subjects.

Variable (units)	Dyslexic group: mean (SD)	Control group: mean (SD)	*p* value
Age (years)	30.4 (9.4)	30.5 (10.6)	Not significant
WAIS-R similarities (standard score)	12.5 (2.2; $n = 15$)	11.9 (1.2; $n = 15$)	Not significant
WAIS-R picture arrangement (standard score)	13.6 (2.0; $n = 15$)	13.2 (1.7; $n = 15$)	Not significant
WAIS-R digit symbol (standard score)	9.0 (2.2)	11.9 (2.1)	$p < 0.001$
WAIS-R digit span (standard score)	10.0 (2.8)	12.7 (2.6)	$p = 0.002$
WRAT reading (standard score)	95.3 (14.3)	117.3 (6.8)	$p < 0.001$
WRAT spelling (standard score)	88.1 (16.4)	112.6 (8.9)	$p < 0.001$
Nonword reading accuracy (errors, maximum 30)	8.0 (6.5)	1.1 (1.5)	$p < 0.001$
Nonword reading time (sec)	56.9 (47.2)	25.2 (8.4)	$p < 0.01$

For the dyslexic group $n = 21$ and for the control group $n = 23$ unless otherwise stated.

was fitted with a Weibull function [42], and threshold was calculated as the FM depth at which the subject correctly identified the target tone in 75% of trials.

Sounds were presented at a comfortable level, about 50–60 dB sensation level, determined by the subject's pure tone audiogram. The duration of each tone was 1000 msec, with a 500 msec ISI between tones. Stimuli were gated on and off with 20 msec rise/fall times. FM in the target was sinusoidal, and detection threshold measurements were made at each of three FM rates: 2 Hz, 40 Hz and 240 Hz. For experiments at 2 Hz and 40 Hz, the carrier frequency was 500 Hz. At 240 Hz, the carrier frequency was 1 kHz. We used different carrier frequencies to ensure that the subjects based their decisions on the presence of FM rather than on other cues from the spectral sidebands which become detectable at high modulation rates with a lower carrier frequency.

Coherent motion paradigm

The RDK stimuli comprised a patch of 150 high luminance (average = 96.9 cd/m^2) white dots (1 pixel) presented on the nominal black background (average = 5.2 cd/m^2) of a computer display. At a constant viewing distance of 57 cm, the patch subtended 7° by 7°, centred on the fovea. Michelson contrast [(Lmax – Lmin)/(Lmax + Lmin)] between the stimulus patch and the background was held at a constant 89.8%, with viewing conducted in a dark room under mesopic luminance conditions (space averaged luminance was about 1.8 cd/m^2). The percentage of coherently moving dots (angular velocity = 8.8°/sec) within a given software animation frame (duration = 50.1 msec) was controlled and varied adaptively to the subject's detection threshold by custom software designed for personal computers. The threshold percentage for coherent motion was defined as the proportion of dots required for the subject to detect either rightward or leftward coherent motion. The non-coherent dots moved randomly between frames in a Brownian manner. In order to eliminate the possibility of detecting the direction of coherent motion by following a single dot, each dot had a fixed lifetime of four animation frames (200.4 msec) after which it would disappear before being regenerated at a random place within the stimulus patch. Percentage of coherent motion is corrected for finite dot lifetimes so that in the case when all dots are moving coherently during a given animation frame and the dots have a lifetime of four frames, this is described as 75% coherence. The total stimulus duration was 18 animation frames or 901.8 msec.

The subjects were asked to fixate a cross that preceded the appearance of the stimulus patch and remained in the centre of the RDK for the entire stimulus duration. After termination of the stimulus, the subject reported the direction of perceived coherent motion by pressing an appropriate key and was instructed to guess when necessary. Coherent motion was varied to the subjects' motion detection threshold by a 3-dB-up to 1-dB-down, two-alternative forced-choice staircase procedure [43]. Thresholds were defined as the geometric average of the last 8 of 10 reversal points within a given series of trials. Each series was repeated at least three times with the mean of these series comprising the subject's overall motion-detection threshold.

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