

Research report

Auditory perceptual grouping and attention in dyslexia

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Abstract

Despite dyslexia affecting a large number of people, the mechanisms underlying the disorder remain undetermined. There are numerous theories about the origins of dyslexia. Many of these relate dyslexia to low-level, sensory temporal processing deficits. Another group of theories attributes dyslexia to language-specific impairments. Here, we show that dyslexics perform worse than controls on an auditory perceptual grouping task. The results show differences in performance between the groups that depend on sound frequency and not solely on parameters related to temporal processing. Performance on this task suggests that dyslexics' deficits may result from impaired attentional control mechanisms. Such deficits are neither modality nor language-specific and may help to reconcile differences between theories of dyslexia.

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1. Introduction

Dyslexia severely afflicts at least 5% of school age children and often persists through adulthood [6,26,28]. While there are many theories about the origin of dyslexia, for expediency, the theories can be divided into two categories: phonological and temporal sensorimotor [28,29,34,43,48]. Phonological theories, which have a long history in linguistics, put forth that irregularities in parts of the brain associated with language processing underlie dyslexics' difficulty to properly represent, store and/or retrieve the constituent sounds of written words [28,29,43].

The difficulty in properly mapping the constituent sounds of oral language would affect the phoneme to grapheme mapping critical for reading [29,43]. This deficit is hypothesized to arise from at least a congenital cortical impairment of the left perisylvian region [12,13,17,42]. Proponents of phonological theories view dyslexia as a language-specific impairment [28,31,36].

Contrasting phonological theories, sensorimotor theories put forth that basic auditory, visual and motor impairments underlie dyslexia. Such sensorimotor deficits have been documented and have focused on less-developed temporal processing abilities in dyslexics [28,29,34,48]. This has been interpreted to support the magnocellular theory of dyslexia, which proposes that rapidly presented sensory stimuli (from visual and auditory modalities) cannot be processed quickly and blur in time because of irregularities in large ('magnocellular') neurons in the thalamus [21,32,35,38]. The magnocellular neurons are thought to play a role in temporal processing because the biophysical proper-

Abbreviations: ISI, Δf

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ties of large cells make them better-suited to respond quickly and precisely in time, and single neuron recordings have shown magnocellular neurons to be more temporally precise than small neurons [34]. Sensorimotor theories, accordingly, can be simplified into theories that dyslexics have low-level sensory temporal processing deficits, and some studies have found a link between these temporal (and spatio-temporal) sensory deficits and reading [38,46]. Attempts to link these deficits to dyslexia have been made by arguing that impairment in low-level sensory temporal processing degrades sensory input for proper phonological coding which is important for reading, thereby leading to language difficulties [10,23,39]. In support of this theory, training techniques aimed at improving dyslexics' auditory temporal processing abilities [24] have shown improvements in their language and possibly reading abilities [40,41].

However, those that view dyslexia as a language-specific impairment have not been convinced [28,31,36], interpreting the results of the behavioral training techniques as being due to improvements based on variables such as concentration rather than specifically treating the dyslexic deficit [31]. Alternatively, associations between impaired phonological awareness and reading problems exist (for reviews, see [3,20]) but a causal relationship has not yet been established for impaired phonological awareness causing reading problems [3]. Although some investigators acknowledge that the proponents of the phonological theory will also have to address the sensorimotor deficits documented in dyslexics, others argue that the phonological theory is regaining ground, in part because these sensorimotor deficits (1) are not always associated with the more prominent phonological deficits and (2) tend to occur only in a fraction of dyslexics that are over sampled in studies promoting the temporal theory [28,30]. Nevertheless, conclusive evidence in support or in refutation of either phonological or temporal processing theories has remained elusive.

Competing views of dyslexia might be reconciled within an alternative theoretical framework. For instance, Hartley and colleagues suggest that processing efficiency, which encompasses such factors as attention, cognition and motivational factors, could account for almost all of the studies reporting sensorimotor deficits [16]. Furthermore, attention-based hypotheses have recently been re-evaluated in both visual and auditory domains. In the visual domain, attentional explanations can strengthen what can be seen as unreliable magnocellular deficits in dyslexics [33], and attention working through the magnocellular visual pathway can help to explain why the magnocellular system would be affected in dyslexia when these neurons cannot support the visual resolution necessary for identifying letters in words [44]. Attention-based hypotheses of dyslexia have also recently been incorporated into the Sluggish Attentional Shifting theory of dyslexia [SAS: [15]] which proposes that dyslexics have 'higher-level' perceptual impairments that

are neither language nor modality-specific, but, rather, are related to mechanisms of attention [7,8,15]. These impairments can be considered higher-level in part because they likely involve the posterior parietal [15] and frontal cortical regions implicated in attention [27]. Recent work has extended SAS theory by attempting to elucidate the underlying mechanisms of attention impairment and determining if other processes (such as memory) are involved. However, further work is needed to elucidate the mechanisms of dyslexics' higher-level perceptual impairments in order to evaluate and/or extend these alternative explanations of dyslexia. This paper explores these alternate ideas by investigating the role of attention in a perceptual grouping experiment and comparing auditory perceptual grouping in dyslexics and normal readers.

Auditory perceptual grouping refers to the ability to disentangle distinct acoustic 'objects' (which one can separately attend) from the complex waveform arriving at each ear [2,25,37]. For example, perceptually grouping the oboes and violins in a musical piece allows one to separately attend to the melodic line of each instrument. Several perceptual grouping studies have shown differences between dyslexics and controls [18,37]. In this study, we used a non-linguistic 'auditory perceptual grouping' paradigm [25]. Participants listened for the presence of a 'middle' frequency tone within a stream of background tones (see Fig. 1A). A deviant 'high' frequency tone was also presented either right before or after the middle frequency tone (Fig. 1B). As the high tone gets *further* in frequency from the middle tone, the middle tone is less likely to be grouped with it and more likely to be grouped with and perceptually 'captured' by the background (Fig. 1C, bottom), leading to difficulty detecting the order of the middle and high tone [25]. Importantly, this perceptual capture taps high-level perceptual grouping mechanisms because it cannot be explained solely by 'local' frequency interactions but must involve the participation of central neurons that demonstrate broad frequency integration [25]. We hypothesized that dyslexics' performance with the same stimuli would be consistent with stronger perceptual capture than for controls. If so, these performance deficits will depend on the spectral, rather than solely the temporal² features of these sounds [25,37]. Furthermore, we hypothesized that performance on this perceptual grouping task will depend on directing stimulus processing and attention towards a specific spectral or frequency region in the

² Here, we use the term 'spectral' to refer to a time scale used to determine a sounds' frequency or spectral composition, such as the frequency content of a single syllable (≥ 100 Hz), whereas 'temporal' refers to slower modulations in time, on a time scale similar to stringing together several syllables or words (≤ 100 Hz). Although it could be argued that auditory spectral information is a fine form of temporal information, the spectral and temporal distinctions are well grounded in auditory research. The boundary can be drawn roughly where amplitude modulation changes from being perceived as pitch to time pulsations that roughly correspond to the temporal cutoff at which inferior colliculus and auditory cortical neurons [5] cannot temporally lock to stimuli.

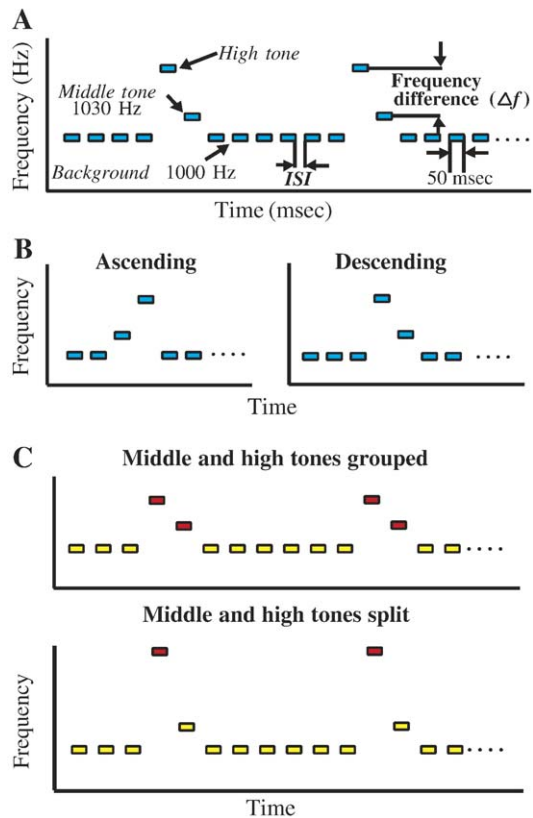


Fig. 1. Schematized spectrographs (frequency vs. time plots) of stimuli. Panel (A) shows a three-frequency stimulus. Background, middle, and high frequency tones are identified (small rectangles), as are the two independent variables: the frequency difference between the middle and high tones (Δf , Hz) and the inter-stimulus interval (ISI, ms). Different Δf s were achieved by manipulating the high tone frequency *only*. Panel (B) shows the possible order of the middle and high tones as ascending (increasing frequency) or descending; order, ISI and Δf were fixed within a trial. Panel (C) depicts the perceptual effect as Δf increases and shows how tones are grouped, with yellow (lighter) and red (darker) filled rectangles (tones) distinguishing two groups. With low Δf s, the middle and high tones are grouped together (red); with large Δf s (lower panel in C) the middle (yellow) and high (red) tones are perceived as belonging to different auditory objects with the middle tone being ‘captured’ or grouped with the background frequency (also yellow).

sounds. Specifically, the deviant high frequency tone can be thought of as an invalid attentional cue that shifts the focus of attention away from the spectral region necessary for detecting the middle frequency tone. Consistent results would support the idea that sensory problems encountered by dyslexics stem from problems involving the control of attention.

2. Methods

2.1. Participants

Nine adult dyslexics (5 female, 4 male) and 10 adult controls (6 female, 4 male) served as participants. The

participants were undergraduate or graduate students at the University of California, Davis (mean age = 22.9 years), recruited by advertisements distributed throughout the campus. Group membership was determined by self-referral with documentation of a prior clinical diagnosis of dyslexia. We confirmed the overall group memberships by documenting a discrepancy between general non-verbal intelligence using the Matrix Analogies Test (The Psychological Corp.; no difference between groups, ANOVA, $P > 0.05$; mean (SD): 64.0 (20.4), dyslexics, 79.8 (16.4), controls) and reading rate (silent passage reading, expressed as grade level standardized percentile rank) using the Nelson–Denny Reading Test (Riverside Publishing Co.; groups differed, ANOVA, $P < 0.001$; mean grade level standardized percentile and SD: 12.2 (19.1), dyslexics, 56.7 (20.7) controls). In order to avoid group selection bias, for which previous work has been criticized [31], we did not assign participants to group on the basis of reading and intelligence levels. Language comprehension was also tested (Nelson–Denny Reading Comprehension Test: groups differed, ANOVA, $P < 0.01$; mean grade level standardized percentile and (SD): 40.9 (36.2), dyslexics, 84.2 (8.9) controls).

A questionnaire was used to verify that participants’ hearing was normal (no history of abnormal audiograms), that they were not at risk for high-frequency hearing loss (e.g., minimal exposure to intense sounds like gun-shots, loud concerts and work in noisy environments) and were not suffering from a flu or cold during the hearing experiments. At the start of the experiment, we also verified that participants could hear all of the tone frequencies used (see below). Individuals pursuing musical degrees were also excluded from the study. Written informed consent was obtained after the nature and consequences of the study were explained pursuant to our protocol which was approved by the human participants’ Internal Review Board at the University of California, Davis.

2.2. Apparatus and stimuli

The study consisted of two experimental sessions (240 trials each on separate days) and was conducted in a darkened, sound attenuated booth (IAC), foam-lined to reduce echoes and external noise. The sound stimulus within a given trial consisted of a series of tones (Fig. 1; for a demonstration of the sounds used and example trials, see http://neuroscience.ucdavis.edu/grads/cipetkov/ms_demo.htm). Three-frequency trials consisted of the following: (1) repeating, fixed frequency 1000 Hz ‘background’ tones, (2) a fixed frequency 1030 Hz ‘middle’ tone and (3) a variable frequency ‘high’ tone presented as shown in Fig. 1A. Two-frequency trials consisted of a replacement of the middle tone with either a background tone or silent gap. Two- and three-frequency trials were balanced and randomly interleaved. In this paper, we report on results from three-frequency

trials. From trial to trial, we varied the frequency difference (Δf) between the middle and high tones (the Δf s used were 28, 117, 471, 1887 and 7551 Hz) and the inter-stimulus interval (ISI: 25, 75, 125 and 225 ms; see Fig. 1A). Δf was varied by changing the frequency of the high tone only. The frequencies and ISIs were chosen such that inferior colliculus and cortical neurons could not encode frequency by phase locking but could encode the ISI by temporal following of single neuron responses [5]. Furthermore, the middle and high tone could either ascend or descend in frequency (ascending or descending order, Fig. 1B).

Tone durations were 50 ms, including 5 ms cosine shaped onset and offset ramps. Tones were 55 dB SPL in intensity (Bruel and Kjaer 2231) and were presented using a TDT System II over Sennheiser (HAD-200) headphones or over a loudspeaker (Radio Shack PA-110). There were no differences in performance contingent on speaker condition.

2.3. Task

On a two-alternative forced choice task, participants initiated each trial (by pressing a button) and then identified the number of tone frequencies perceived in a sequence consisting of two or three frequencies (Fig. 1). The participants were told to listen to the sequence of tones and identify if they heard one or two tone frequencies outside of the background tones' frequency—which would be present during each trial. Therefore, participants responded to hearing the two or three frequencies in the sequence of tones by pressing one of two buttons. On a trial, a tone sequence continued until 5 to 8 middle and high tone pairs, each separated by 6–12 background tones, were presented. A trial terminated after a response was made following the presentation of the first pair of middle and high tones. Visual feedback (color LEDs) informed participants of correct and incorrect responses. Before the first testing session, participants completed practice trials (with the longer ISIs) until they felt confident with the task; this also served to confirm that they were able to hear all of the tone frequencies used in the experiment.

3. Results

3.1. Analyses

Performance was measured by how often participants correctly detected the presence of three frequencies (proportion correct). The statistical analysis used was a 3-way analysis of variance (*group* by ISI by Δf) with repeated measures (RM-ANOVA) on the two within-subject factors: ISI and Δf . The design of the experiment and analysis allowed us to independently determine the contribution of the two variables, ISI and Δf , along with possible higher order interactions. The between-subjects factor was group

(dyslexics and controls). Huynh–Feldt epsilon (ϵ) corrections were used when appropriate [19]. For order analyses (ascending vs. descending, see Fig. 1), we used a similar RM-ANOVA with *order* as the third within-subjects factor. Entering *gender* as a between-subject variable into these analyses showed no effect for *gender* ($P > 0.5$), and *gender* interactions were likewise not significant in any of the analyses reported.

3.2. Perceptual capture

Dyslexics performed worse than controls, and the difference depended largely on the frequency of the high tone and not solely on the presentation rate (ISI). Dyslexics' poorer overall performance was significant [*group* effect: $F(1, 17) = 11.09$, $P < 0.01$]. Differences in performance between dyslexics and controls occurred mainly at higher Δf s (Fig. 2) [*group* by Δf : $F(4,68) = 3.10$, Huynh–Feldt Epsilon (ϵ) = 0.63, $P < 0.05$]. There were no significant differences between groups as a function of ISI [*group* by ISI: $F(3,51) = 0.67$, $\epsilon = 0.56$, $P = 0.46$]. Therefore, the main effect on dyslexics' performance was based primarily on Δf rather than solely on ISI.

There was an interaction between ISI and Δf in the analysis that was not group-specific [ISI by Δf , $F(12,204) = 2.03$, $\epsilon = 0.81$, $P < 0.05$]. This interaction seems to reflect the flattening of the curve at the longest ISI of 225 ms (Fig. 2A) and is consistent with the perceptual capture effect, which depends on Δf , occurring mainly at faster presentation rates (i.e., lower ISIs). The group effect for this interaction approached significance [*group* by ISI by Δf , $F(12, 204) = 1.65$, $\epsilon = 0.81$, $0.05 P < 0.1$]. This reflects a larger drop in performance for dyslexics (Fig. 2A), primarily at the higher Δf s and faster presentation rates, consistent with dyslexics being more prone to perceptual 'capture' of the middle tone by the background (Fig. 1). Note that dyslexics' performance for low Δf s was comparable to controls (Fig. 2), ruling out factors such as general difficulties with the task.

3.3. Effects of tone order on capture

Not only did perceptual capture depend on frequency separation, but also on the order of presentation of the middle and high tone. Capture was more likely when the high tone preceded the middle tone (descending order) than when the middle tone preceded the high tone (ascending order). This was observed as significantly worse performance on descending compared to ascending order [Fig. 3A, *order* effect, pooled over all participants: $F(1,17) = 18.04$, $P < 0.001$].

When examined as a function of ISI and Δf , the differences between ascending and descending conditions (see Figs. 3B–C) followed the rules for perceptual capture—that is, capture was more likely at faster presentation rates (shorter ISIs) and higher Δf s. The differences are consistent

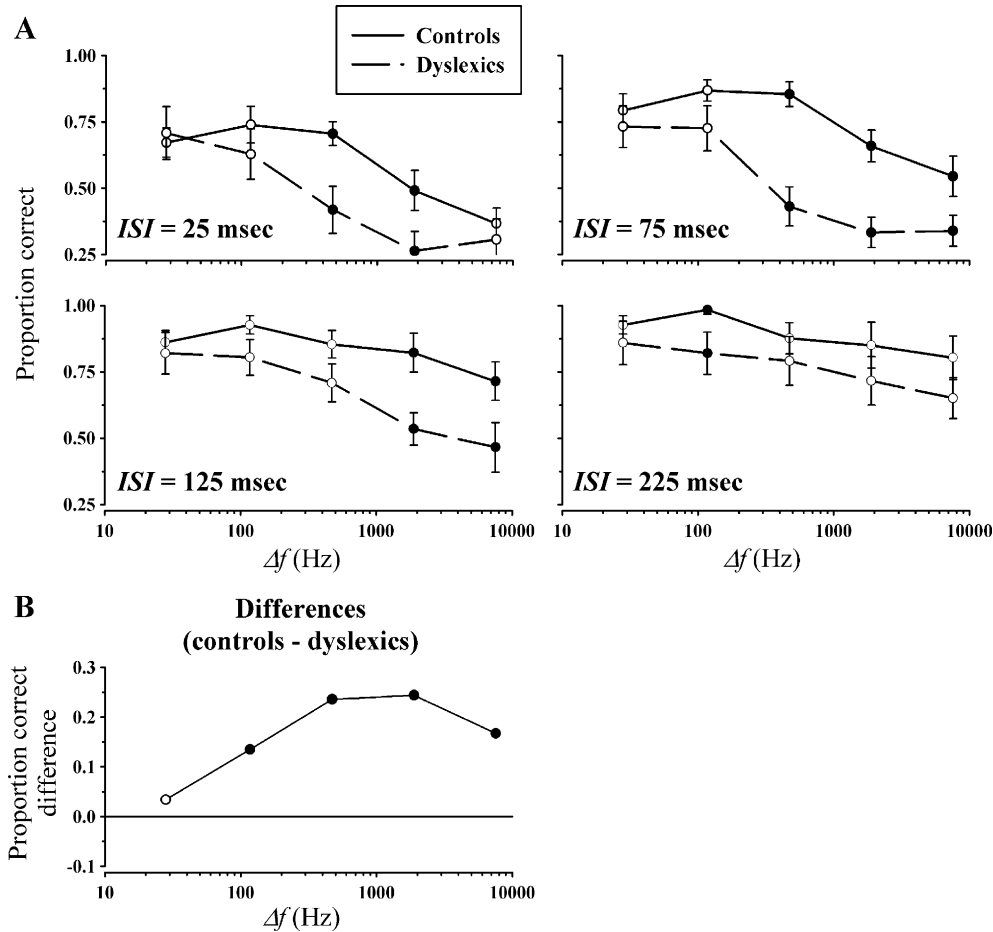


Fig. 2. Controls' (solid line) and dyslexics' (dashed line) performance vs. the frequency difference between the middle and high tones (Δf). Performance is shown as the proportion correct identification (\pm SEM) of the three-tone stimulus. Panel (A) displays performance for the four ISIs. Filled circles depict pairwise estimates (for each Δf) that were significantly different between the groups (two-tailed t tests, $P < 0.05$). Panel (B) shows the differences between the groups pooled across all ISIs. All but the lowest Δf values differed between the groups ($P < 0.05$).

with stronger capture in the descending condition, rather than a general difficulty with the descending sequence independent of ISI and Δf . As expected with capture, the *relative* drop in performance for the descending condition was more pronounced for faster ISIs (Fig. 3B, filled symbols), where capture is more likely (the corresponding RM-ANOVA interaction was significant [*order* by ISI: $F(3, 51) = 4.31$, $\epsilon = 0.94$, $P < 0.01$]). At slower ISIs, where capture is less likely, differences between ascending and descending conditions did not reach significance (Fig. 3B, open symbols). Performance differences between ascending and descending conditions were more pronounced at larger Δf s (Fig. 3C) where capture is occurring, and less pronounced at the smaller Δf s where there should be no capture (the corresponding *order* by Δf interaction approached significance [$F(4, 68) = 2.34$, $\epsilon = 0.69$, $P < 0.1$]). It is important to note that results consistent with perceptual capture are observed with either order (note that in Fig 3C, upper plot, performance for both ascending and descending order drops with increasing Δf and decreasing ISI); capture is just stronger for descending tones. These data indicate that the high tone is influencing the observer's

ability to accurately identify the middle tone's frequency and that this influence is greater when the high tone precedes the middle tone than when it follows the middle tone.

Dyslexics' overall performance was worse than controls', and dyslexics were proportionally worse for both ascending and descending sequences. In other words, the *order* by *group* interaction was not significantly different between dyslexics and controls [$F(1,17) = 1.45$, $P = 0.245$]. This result has implications for the type of mechanisms affected in dyslexia and is discussed in Sections 4.2 *The relationship of perceptual grouping to dyslexia: lack of an 'order by group' interaction* and 4.4 *Relationship of the results to attentional deficits*.

3.4. Association between reading rate and performance

We wanted to define a single measure to characterize the relationship between reading rate and performance on this perceptual grouping task. Determining one metric, from the many time and frequency data points, allows for a more economical and intuitive description of performance by

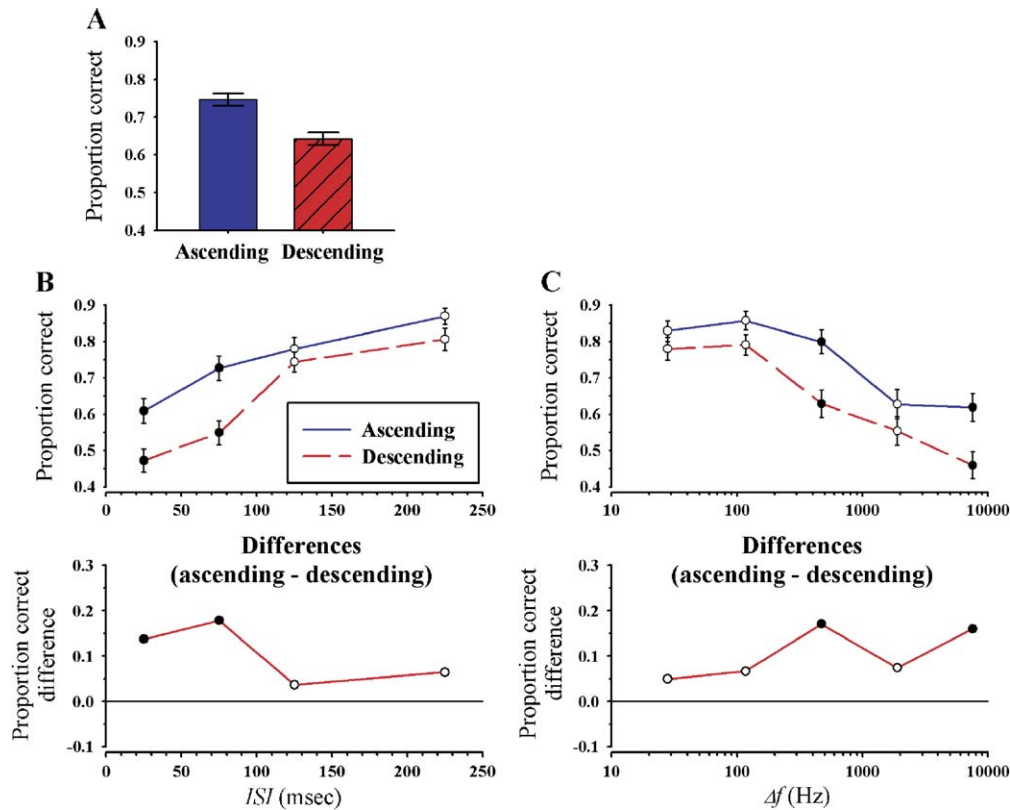


Fig. 3. Performance based on the order of the middle and high tones. (A) Dyslexics and controls performed worse (proportion correct \pm SEM) when the middle tone followed the high tone (descending order—stippled red bar) than when the middle tone preceded the high tone (ascending order—blue bar). (B) Ascending (solid blue line) vs. descending (dashed red line) performance is shown as a function of *ISI* (B) and Δf (C). For panels (B) and (C), significant differences between conditions (*ISI* and Δf , respectively) are depicted with filled circles (two-tailed *t* tests, $P < 0.05$).

providing a single parameter to link to reading rate (Fig. 4A). However, because many metrics can be derived from these data, we chose the one that would reflect the most robust performance decrement between dyslexics vs. controls (i.e., the point that is more likely to reflect different perceptual groupings by the two groups), while also controlling for participants' general performance at a level that was comparable between the groups. Therefore, to determine this metric, we defined a measure of performance decrement at an *ISI* of 75 ms as the difference between the first or lowest Δf (where dyslexics and controls did not differ, see Fig. 2) and the third Δf (the point at which dyslexics and controls most differed). Higher values of performance decrement indicate a larger drop in performance (Fig. 4). We observed a significant association for all participants between reading rate (expressed as percentile rank) and the measure of performance decrement (Nelson–Denny Reading Test; $r = -0.520$, $P < 0.05$, see Fig. 4A). In contrast, there was not a significant association between this performance measure and visual/spatial intelligence (Matrix Analogies Test; $r = -0.338$, $P = 0.157$). Language comprehension, on the other hand, showed a trend with performance ($r = -0.410$, $P = 0.08$). These results demonstrate a strong association of perceptual grouping to reading impairments, but not to visual/spatial intelligence.

We were also interested in determining the amount of overlap between group distributions of this performance measure. We observed that 58% (11/19) of participants did not overlap and thereby performed outside of the range of the other group (Fig. 4B). Six out of nine dyslexics (67%) performed outside of the range of controls. Alternatively, only 3 dyslexics performed within the range of controls (33% overlap: 3/9) and 5 controls performed within the range of dyslexics (50%: 5/10), also see Fig. 4C (distribution mean (SD): 0.30 (0.26), dyslexics; -0.06 (0.14), controls).

The distributions of performance decrement for the dyslexics in comparison to controls in Fig. 4C resemble a signal from noise problem, so we determined how well an ideal observer could assign participants to the correct group given their performance (an analysis that is based on Signal Detection Theory [SDT: [14]]). This result is reported in Fig. 4D and is based on the distributions of performance decrement in Fig. 4C. Obtaining the dashed line function in this plot is analogous to an ideal observer adopting different criteria for judging whether a participant belonged to the dyslexic group. For instance, when the ideal observer uses a strict criterion of >0.24 performance decrement (i.e., participants to the right of arrow (a) in Fig. 4C), over 55% of dyslexics can be correctly classified (see (a) in Fig.

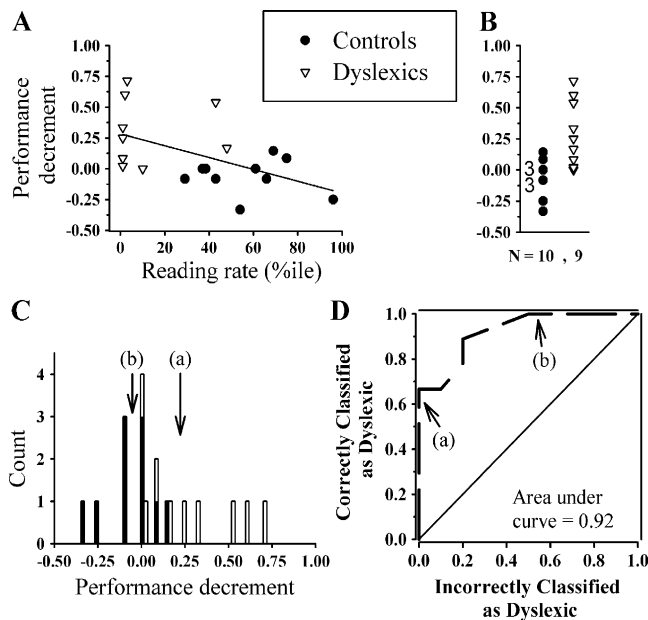


Fig. 4. Group performance and association with reading rate. Panel (A) shows the association between reading rate (grade level standardized percentile rank: percentile) from the Nelson–Denny Reading Test and a measure of capture ('performance decrement'—the difference between the first (lowest) and third Δf at an ISI of 75 ms, see Results). Filled circles depict control and open triangles dyslexic participants in panels (A–B). Panel (B) scatter plot of the group distributions on the measure of performance decrement—numbers identify where multiple individuals obtained the same performance. (C) Stacked bar graph of the performance distribution with controls represented by black and dyslexics by white bar segments. Panel (D) shows the results of an ideal observer model in classifying a participant as dyslexic versus control. The dashed line function is based on the performance distributions in panel (C), see text for details.

4D), and no controls are incorrectly classified as dyslexic. By loosening the criterion and allowing slightly better performance to be classified as dyslexic, the ideal observer can boost the correct classification of dyslexics up to 100% (y axis in Fig. 4D, also see (b) in Fig. 4D) at the expense of incorrectly classifying some controls as dyslexics (x axis in Fig. 4D). For example, if a performance decrement of ≥ 0.05 is used (see (b) in Fig. 4D), all the dyslexics are correctly identified and 5/10 controls are misclassified. Therefore, as the criterion is lowered toward better performance, the dashed line function in Fig. 4D moves from the lower left corner (passing point (a)) to the top right corner of the plot (passing point (b)). The area under this curve, also known as the ROC Area in SDT [22], is the probability that the ideal observer correctly assigns a participant to the right group based on this performance decrement. This value (area under curve = 0.92) is much higher than if the distributions completely overlapped [14], which would be an area of 0.50 (diagonal line in Fig. 4D).

A stepwise discriminant function analysis was also used to determine which of 4 variables (the measure of performance decrement, MAT, Nelson–Denny Reading Rate and Comprehension scores) could significantly distinguish the groups. Only reading rate and performance on this task

could significantly ($P < 0.001$) predict group membership (Standardized Canonical Discriminant Function Coefficients: Nelson–Denny Reading Rate = 0.79; performance decrement measure = 0.61). These results show that, although reading rate was the stronger predictor of group membership, performance on this perceptual grouping task could well distinguish these groups of self-reported dyslexics and controls.

4. Discussion

This paper demonstrates differences between controls and dyslexics related to perceptual grouping. The differences significantly depend on sound frequency and not solely on presentation rate, ruling out a simple temporal processing deficit and supporting that dyslexics have a deficit dependent on the spectral *and* temporal features of sounds (i.e., a 'spectro-temporal' deficit [37,46]). Perceptual capture is more pronounced with descending than ascending tone frequency, which implies that attention is critical in this grouping paradigm. Because of this result, we postulate that problems in directing attention might be responsible for the stronger susceptibility to capture found in dyslexics. Furthermore, because some of our conclusions regarding dyslexia rest on new results prompting a reinterpretation of auditory perceptual grouping, the discussion will first focus on the link between perceptual grouping and attention, and only later attempt to relate this to dyslexia.

4.1. Order effects in relation to perceptual grouping and capture

An important finding of this paper is that perceptual capture was stronger for descending than ascending order. To our knowledge, no one has investigated the effects of order of frequency presentation on perceptual grouping and stream segregation³. Even if dyslexics were not participants in this study, the order results have a significant impact on our understanding of the relationship of perceptual grouping to Gestalt rules and attention. Therefore, it is important to consider this finding independent of the two participant groups in this study. The results indicate that attention-related capture might be inextricably tied to grouping and that attentional mechanisms can explain some aspects of perceptual grouping that cannot be explained by Gestalt principles.

Two Gestalt rules related to this grouping paradigm are that (1) rapidly presented tones that are also (2) disparate in frequency are likely to be assigned to differing perceptual groups or objects. Another general principle is that order discriminations are easier within than across groupings [2]. These rules can be used to

³ Stream segregation is a term commonly used to refer to the perceptual segregation and grouping of tone sequences.

explain, in part, the results of a previous study [25] where participants were asked to detect the order of the middle and high tones, and performance dropped as a function of increasing Δf and faster presentation rates. The result at large Δf s and fast presentation rates can be explained by the middle tone being captured by, and grouped with, the background. Since order determination is difficult across perceptual groups, it should be difficult to tell the order of the middle and high tones, because they belong to different groups.

The present study, however, makes new findings that suggest that this framework is not the entire story. First, Gestalt principles only predict that the middle tone will be grouped with the background tones. At relatively high presentation rates, three tones with distinct frequencies should be heard, but the listeners should not be able to perceive their order. By asking participants to report the number of frequencies present, rather than tone order, we have uncovered an effect based on the order of the sequence presentation not previously reported and outside the scope of current perceptual theory. Second, the Gestalt framework cannot be used to explain why ascending or descending order should be more difficult. The theory predicts that just temporal rapidity and frequency similarity are important, and within that context the ordering of the tone sequence should not make a difference.

As an alternative to a simple Gestalt-based explanation, it seems parsimonious to explain these results in terms of the ability of the salient high tone to act as an attentional attractor. We propose that the high tone ‘grabs’ attention, thereby directing it away from the middle tone, muddling the ability to discriminate middle from background tone frequency. By repeatedly presenting 1000 Hz background tones, attention is automatically focused on frequencies near 1000 Hz. Additionally, participants should be focusing their concentration and processing resources on the background/middle frequency range because experience on previous trials has indicated that the middle tone is difficult to discriminate from the background. However, when the deviant high tone is encountered, attention and associated processing resources are pulled away from the spectral region of the background/middle tones thereby decreasing the ability to distinguish background from middle tone frequencies. When the high tone precedes the middle tone (descending order), this strongly affects the ability to process the subsequent middle tone because it takes time to re-direct attention to the 1000–1030 Hz region. On the other hand, when the high tone follows the middle tone (ascending order), performance would be less impaired because the distracting effect of the high tone is encountered when much, but not all, of the processing of the middle tone has already occurred. However, it is important to note that, even in the ascending condition, performance at high Δf s should be affected because the high tone will interfere with the completion of processing of the middle tone.

4.2. The relationship of perceptual grouping to dyslexia: lack of an ‘order by group’ interaction

That (1) the employed experimental paradigm likely taps attention and (2) dyslexics are impaired in this paradigm support that dyslexics have attentional problems. It is important in forming this argument that points (1) and (2) be independent of each other; that is, that (1) argues about the nature and mechanisms of the task in general (independent of dyslexia) and (2) argues that, given that this perceptual grouping is tied to attention, stronger capture in a group of participants argues for a difference in their attentional processing.

It might seem counterintuitive, then, that there were no group differences between dyslexics and controls on order (an *order by group* interaction). In the following discussion, we reveal that such an interaction is not necessary for supporting that dyslexics’ performance on this task involves difficulties with attention.

An interpretation based on a significant *order by group* effect in its simplest form might be based on the assumption that forward effects of the distracting high tone influence attentional related capture, but backward effects do not. In this extreme case, one would think that dyslexics would be impaired, relative to controls, for descending order where attentional capture occurs, but not on ascending order where the assumption is that there is no attentional related capture. However, this assumption is not valid because in Figs. 3B and C it is apparent that for both ascending and descending order capture occurs; it is just the magnitude of the capture that differs. For descending order, there is larger capture because attention is affected from the beginning of the middle tone, whereas for ascending order some processing of the middle tone can occur before attention is deflected. Therefore, both the forward and reverse effects appear to be attention-related.

Alternatively, one could try to argue that where capture is stronger dyslexics should be more impaired; that is, the magnitude of the impairment scales with the magnitude of capture. Using this rationale, one would predict that the lines for ascending and descending performance in Fig. 3 should diverge as ISI decreases and Δf increases. This does not happen, but there is an experimental reason why a result consistent with this argument was not observed. Lower limits in performance for the descending condition (i.e., floor effects) might obscure or, worse, reverse an *order by group* result. For example, if we look at Fig. 2 at an ISI of 25 ms, dyslexics’ performance ultimately drops to a rate of ~ 0.3 proportion correct as a function of Δf . If there is a floor on performance for descending order (e.g., 0 proportion correct), and this starts at $\Delta f = 1887$ Hz, then a drop in performance between $\Delta f = 471$ and 1887 Hz can only be achieved by further drops in performance for the *ascending* order (descending cannot get any worse than the floor). Therefore, a floor effect predicts that at large Δf s the difference in performance between ascending and descend-

ing order (Fig. 3) will *decrease* even though performance continues to drop (Fig. 2). Furthermore, if at this Δf (e.g., $\Delta f = 471$ or 1887 Hz in Fig. 2, $ISI = 25$ ms) performance by controls can still drop for both orders because they have not reached the floor, dyslexics will appear to be showing *smaller* differences than controls as capture get stronger. Thus, this line of reasoning also reveals that a significant *order by group* effect could run counter to an expectation that dyslexics would have an increasing difference on the descending order. In other words, if there is a general tendency for larger performance differences under conditions where capture is stronger, floor effects will counteract the tendency and would at least make differences difficult to detect. Therefore, even if one presumes that the magnitude of impairment in dyslexia scales with the magnitude of capture, the lack of the *group by order* interaction does not argue against an attentional deficit in dyslexia.

A simpler explanation may be preferable for the entirety of our results. The data support the interpretation that the perception of both ascending and descending orders depends on attention and that dyslexics' attentionally related deficits, in comparison to controls, are manifested about equally in both cases. For example, if when capture is present, the descending vs. ascending order *difference* is always 0.20 proportion correct for either group, then the two groups would show the same difference in performance; this is consistent with the results (that is, there is no *order by group* effect and the line plots of Fig. 3 appear parallel for shorter ISIs and larger Δf s).

4.3. Relationship of the results to low-level temporal processing and language-specific deficits

Neither low-level temporal processing [10,39,48] nor language-specific deficits [28,36] can easily account for the observed results [15,37]. First, poorer performance for dyslexics is significantly related to the frequency or spectral aspects of the stimulus (Δf), but not solely to presentation rate. A purely temporal deficit should cause an equal impairment at all Δf s for the dyslexics and a larger drop in dyslexics' performance relative to controls at faster presentation rates. However, at small Δf s and *all* ISIs (even at 25 ms), dyslexics performed as well as controls (Fig. 2).

These results also cannot be explained by simple, low-level (or peripherally based) masking differences between dyslexics and controls. Simple forward and backwards masking are most pronounced when tones are close in frequency. In this perceptual grouping study, performance gets progressively worse as the high tone gets *further* (up to 3 octaves) in frequency from the middle tone, indicating a higher-level 'global' frequency-processing deficit [25,37]. In this way, these results differ from dyslexics' deficits in simple forward and backward masking which are most pronounced when the masker is *close* to or 'local' in frequency to the probe [47]. Similarly, masking of the middle tone by the background tone cannot account for the

observed results since the frequency relationship between the middle and background tone was fixed in these experiments.

Language-specific deficits also cannot easily explain the results because this task employed tonal stimuli with no linguistic content. We also showed an association between performance on this non-linguistic task and reading rate, and performance on this task could be used to predict group membership. When taken in combination, these data argue that there is a need for a framework that neither relies solely on low-level temporal processing problems nor solely on a language-specific impairment.

4.4. Relationship of the results to attentional deficits

Our data are consistent with an alternative view that dyslexics' perceptual deficits relate to attentional processes, rather than being low-level temporal or language-specific [1,7,15,44]. Correctly directing attention, which is important for reading [44], is also necessary to analyze noisy environments with multiple sound sources, such as a cocktail party [4] or a classroom, and our perceptual grouping experiment taps into this. In noisy environments with many distracting sounds, one must focus attention on an object of interest to which they wish to listen. Normally, distracting stimuli would have a small effect on performance, but a 'salient' stimulus that captures attention could impair performance greatly. The present experiment is like that in that participants need to focus on the middle tone's frequency, but the salient high tone pulls attention away from the middle tone's frequency. Our results are consistent with dyslexics having difficulty in focusing spatial auditory attention [7].

There are two factors that might contribute to the difficulties dyslexics have with focused spectral auditory attention. One is that participants have difficulty re-directing attention to the middle tone after the distracting effects of the high tone. The other potential problem with focused attention is that participants might be more prone to distracting effects of the high tone.

The notion that dyslexics have difficulty re-directing attention to the middle tone after the distracting effects of the high tone is consistent with the Sluggish Attentional Shifting (SAS) theory [15]. This theory proposes that the dyslexics' putative temporal processing deficits stem from sluggishness in the focus of attention to stimulus features, with the posterior parietal cortex being affected. Specifically, the theory proposes that dyslexics have sluggishness in voluntarily directing the focus of attention⁴. Recent

⁴ This voluntary guidance of attention is also called endogenous guidance and involves mechanisms that are considered to be under the observer's control. This is contrasted by automatic or exogenous guidance of attention that is controlled by stimuli in the outside world and is considered to be beyond the observer's control. The distracting effect of the high tone can be thought to be due to exogenous control of attention.

findings of slower focusing in spatial (auditory and visual) attention for dyslexic children support this theory [7]. SAS could also account for why dyslexics require slower presentation rates than controls for comparable performance on many sensory tasks [15]. The results of Fig. 2 are consistent with sluggish spectral attentional shifting because dyslexic performance was similar at the 25 and 75 ms ISIs, whereas the performance of normal readers improved more dramatically. Furthermore, dyslexics' performance at the 125 and 225 ms ISIs was similar to the performance of controls at 75 and 125 ms ISI respectively, suggesting that the guidance of auditory attention is slower in dyslexics than controls. However, the lack of a *group by order* interaction runs counter to SAS theory which would predict more impairment for descending than ascending order in dyslexics and therefore a significant interaction. This negative result cannot be viewed as excluding the specific idea of a sluggish attentional shifting (part of SAS theory) though, because the lack of a *group by order* result could be due to floor effects on performance (see Section 4.2).

The data in this paper we believe are more consistent with an impairment in inhibitory processes of attention. This can be thought of as having difficulty suppressing the effects of stimuli that should not be attended [7], and therefore dyslexics have more difficulty overriding exogenous guidance of attention [9]. This can explain why dyslexics are prone to capture at smaller Δf 's than controls, and the lack of a strong ISI dependency. When the high tone is very far in frequency from the middle tone, *neither* dyslexics nor controls can override exogenous capture of attention, and resources are therefore pulled away from the low/middle frequency; accordingly, neither group can accurately process the middle tone. When the high frequency tone is close to the 1030 Hz middle tone in frequency, both groups can keep their attention focused on the middle/low tone frequency region and therefore easily process the middle tone's frequency. However, when the high tone is moderately far from the middle tone in frequency, the controls can maintain endogenous guidance of attention on the middle tone frequency, but the exogenous effect of the high tone on attention is stronger for dyslexics who cannot keep attention focused on the middle tone.

While our results cannot disentangle how much is due to high frequency tones having a larger distracting effect and how much is due to SAS, at this point, we believe our experiments are more strongly tapping into the former. This interpretation is consistent with other reports that dyslexics have difficulties overriding invalid attentional cues [8] and may have impaired inhibitory attentional mechanisms [7]. The previous work and our results extend SAS theory by identifying potentially impaired attentional mechanisms. The results suggest that, as well as exhibiting difficulties endogenously refocusing attention, dyslexics also appear to have trouble overriding exogenous pulls on the focus of attention. Therefore, endogenous control of attention (even when attention is thought to be focused) appears to be a less

stable process in dyslexia and may contribute to difficulties in completing task-dependent sensory processing such as encoding stimuli into memory.

4.5. Considerations and limitations

Audiograms were not measured as part of this study. Therefore, it is possible that a hearing impairment in the dyslexics could cause the observed results. This is unlikely because if participants in the dyslexic group had poor high frequency hearing, their performance in detecting the middle frequency tone should *improve* in comparison to controls. That is, dyslexics would show less capture than controls. The main result is the opposite, so if there were a high frequency hearing loss (the most common hearing loss found on audiograms), it would only serve to underestimate the magnitude of the impairment in dyslexics.

Another consideration is that this sample of adult dyslexics may not be representative of other groups of dyslexic adults or children. For instance, these dyslexics were pursuing a higher education and may have developed some more efficient compensatory mechanisms for their slower reading abilities in order to compete academically. Support for this was revealed by language comprehension scores only trending with performance on this task (which was highly associated with reading rate) and by language comprehension not significantly predicting group membership. An interesting future direction of this work would be to extend study of this form of perceptual capture to other groups. Such work will likely have to tailor the ISI and Δf parameters to suit the abilities of the dyslexic and control groups being assessed. Future work can also extend our observations to disentangle specific attentional mechanisms that might be impaired in dyslexia.

A third consideration is that the relatively small sample size may have precluded certain statistical interactions from being significant (e.g., the *group by ISI by Δf* which trended, or the *order by group* interaction which was not significant). However, a larger sample should have no bearing on the conclusions drawn from this work, which are based on significant effects. We have also considered other possible outcomes in the case of trending and/or non-significant effects where appropriate. A further consideration in terms of alternative explanations of the results is that there is growing evidence that there are many symptoms associated with dyslexia making it difficult for any one set of theories to explain the etiology of reading impairment. It is possible, for example, that rather than having one etiology, dyslexia can be attributed to heterogeneous problems [10,11,45]. Alternatively, dyslexia could manifest as different symptoms and to different degrees by a common cause suggesting that different theories of dyslexia need not be mutually exclusive [15,44]. In either case, it is still possible to use the prominent symptoms of dyslexia to more effectively identify the neural substrates of the disorder.

Some investigators argued that sensory deficits in dyslexics may have little to do with their prominent phonological deficits, but rather are epiphenomenal symptoms only present in a small subset of the population. Such arguments have been used against the temporal processing theory, as opponents of this theory claim that the deficits are only in a small subset (~25%) of dyslexics [30,31,45]. They argue that it would be difficult to explain a heterogenous disorder such as dyslexia by relying on the temporal processing impairments of a small fraction of dyslexics [30]. In relation to this study, however, it seems unlikely that we are observing an epiphenomenal impairment of sound perception in a heterogenous disorder or an impairment that has little to do with dyslexics' language-specific problems. We show here that this paradigm may sample from a larger portion of the dyslexic population because 67% of dyslexics performed outside of the range of controls. Furthermore, an ideal observer model based on our data had a high probability (0.92) of correctly classifying a dyslexic based on their performance on this perceptual grouping task. Therefore, this perceptual grouping deficit seems common in this sample of poor readers.

4.6. Generalization of attention problems to sensory and language processing

Because attention is paramount in effective sensory and language processing, attentional problems are ideal for unifying and strengthening different theories on the etiology of dyslexia. The results suggest that dyslexics' difficulties on this task relate to their ability to direct attention to a specific *frequency*. However, attentional deficits under different conditions need not be limited to frequency processing but can also affect the directing of attention towards specific locations [7] and frequencies in time [18]. Attention modulates many different brain areas, so an attentional deficit could extend to other aspects of sensory and language processing in multiple brain areas (both sensory and language-related areas), possibly in parallel.

In conclusion, by choosing a psychophysical task that is neither low level nor language-specific, we were able to tap into a higher-level perceptual deficit that might cross modalities and explain both auditory receptive language problems as well as reading problems encountered by dyslexics. Although it would be difficult to prove that this higher-level perceptual deficit causes the language-related problems encountered by dyslexics, it is parsimonious to argue that problems directing attention would cause difficulties with speech and language processing. This is because language reception, whether it is hearing or reading, inherently requires constantly processing sequenced information, using recent history to predict or emphasize likely future or recently occurring patterns. In other words, it requires constant predictive and retrospective processing of sensory stimuli and symbols, a process that is enhanced by correctly guiding one's attention [44]. That the proposed

problems with exogenous attention would span both visual, auditory, and language processing further adds to the attractiveness of this idea.

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