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Wide and diffuse perceptual modes characterize dyslexics in vision and audition

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Abstract. We examined the performance of dyslexic and typically reading children on two analogous recognition tasks: one visual and the other auditory. Both tasks required recognition of centrally and peripherally presented stimuli. Dyslexics recognized letters visually farther in the periphery and more diffuse near the center than typical readers did. Both groups performed comparably in recognizing centrally spoken stimuli presented without peripheral interference, but in the presence of a surrounding speech mask (the 'cocktail-party effect') dyslexics recognized the central stimuli significantly less well than typical readers. However, dyslexics had a higher ratio of the number of words recognized from the surrounding speech mask, relative to the ones from the center, than typical readers did. We suggest that the evidence of wide visual and auditory perceptual modes in dyslexics indicates wider multi-dimensional neural tuning of sensory processing interacting with wider spatial attention.

1 Introduction

Reading is a highly complex and integrative process. It involves precise visual recognition of letters, letter combinations, and words, together with the skill for converting the seen forms to their appropriate sounds. This conversion requires phonological skills and the rules for letter/sound conversion. In addition, reading requires adequate knowledge of the language one is reading and the ability to extract the meaning from visually presented words. This highly integrative process depends on reliable multi-faceted visual and auditory sensory processing (for recent reviews, see Boden and Giaschi 2007; Wright et al 2000).

In general, sensory processing interacting with stimulus-driven spatial attention forms the pre-cognitive stage on which cognitive processing is based. Failure or inadequate processing in the pre-cognitive level might result in difficulties in reading (Boden and Giaschi 2007; Wright et al 2000). In order to achieve adequate proficiency in reading, much tutoring and practice are required (eg Hutzler et al 2004). However, some children are unable to achieve the normal level of reading in spite of ample tutoring, normal intelligence, and absence of overt pathologies; their condition is known as developmental dyslexia (dyslexia, in short) or as specific reading disability. Although the field lacks an agreed precise definition of dyslexia, it is generally accepted that severe retardation of reading is common to all dyslexics.

Most commonly, dyslexia is described as a language-based disorder of phonological processing and phonemic awareness. This is referred to as the 'phonological model' (eg Liberman et al 1974; Lyon 1995) of dyslexia and it postulates that dyslexics have a specific impairment in storage, representation, and retrieval of speech sounds. Hence dyslexia is considered to be a higher-level cognitive disorder that bypasses contribution to the condition by low-level sensory processing (Ramus 2003). Yet, "no study has provided unequivocal evidence that there is a causal link from competence in phonological awareness to success in reading ..." (Castles and Colheart 2004, page 77). In recent years, a large body of work has attempted to demonstrate sensory processing involvement in dyslexia by correlating specific sensory processing aberration with dyslexia. A prominent theory postulates a generalized magnocellular system deficit (for a review see Stein and Walsh 1997) supported by anatomical and physiological findings (Livingstone et al 1991): visual perception of contrast sensitivity of low spatial frequency gratings (eg Lovegrove et al 1980) and visual perception of coherent motion (Cornelissen et al 1998); auditory perception of transients in temporal processing (Tallal 1980), auditory frequency and amplitude modulations (McAnally and Stein 1996); and tactile perception of gratings (Grant et al 1999).

Also linked to dyslexia are general (visual and auditory) temporal processing deficits (eg Farmer and Klein 1995) that in parts are included in the magnocellular hypothesis. However, it has been estimated that a large fraction of typical readers have deficits that can be attributed to the magnocellular system, without having reading deficits (Skoyles and Skottun 2004). In addition, there is accumulating evidence to show visual and auditory sensory deficits in dyslexics that cannot be attributed to the magnocellular system (eg Amitay et al 2002), and that some results that point to the magnocellular deficit could also be explained by inattention (Stuart et al 2001).

In general, visual spatial attention is known to modulate the neural representation of the attended stimuli (see Reynolds and Chelazzi 2004 for a recent review), such as contrast sensitivity (Cameron et al 2002), texture segmentation (Casco et al 2005), and spatial resolution (Carrasco et al 2002); it also alters appearance (Carrasco et al 2004) and diminishes the effect of noise outside the attended area (Cheal and Gregory 1997). In addition, sound processing and segmentation of speech signals are likely to require rapid and efficient engagement of auditory spatial attention (Renvall and Hari 2002). A deficit in the allocation of visual attention was revealed in poor readers (Brannan and Williams 1987). Other studies have shown prolonged attention dwell time (Hari et al 1999) and sluggish attention shifting in dyslexics (Facoetti et al 2005). The latter was suggested as the "pathophysiological link between neural-level disorders and behavioral deficits in dyslexic subjects that can impair the processing of rapid stimulus sequences in all sensory modalities" (Hari and Renvall 2001, page 531). These findings were supported by evidence showing slower visual and auditory attention orienting in dyslexics (eg Facoetti et al 2005). Rehabilitation studies also suggested a general visuo-spatial attention deficit in dyslexics (Richards et al 1990) pointing to lack of control and inability to inhibit the information of the unattended region (Facoetti et al 2003a). These studies connected the various attentional deficits with the magnocellular system deficit. Some of the psychophysical differences mentioned above and in other studies may also be the basis of the phonological deficits (eg Witton et al 1998). As this review of past work suggests, dyslexia is likely to arise from the contribution of multiple sensory factors rather than just a single one.

1.1 *Masking and perceptual modes*

Most of the observed differences between dyslexics and typical readers were either low-level sensory measures or high-level cognitive ones. However, as sensory processing progresses hierarchically from the less to the more complex, there is still an intermediate yet a highly integrative pre-cognitive processing level that we name perceptual mode. It has been shown consistently that dyslexics have a wider visual perceptual mode than typical readers do and the difference between the groups is highly significant with little individual overlap between the groups (Dautrich 1993; Geiger and Lettvin 1987, 2000; Geiger et al 1992, 1994; Lorusso et al 2004; Perry et al 1989). Geiger and Lettvin (1987, 2000) defined perceptual mode as the pre-cognitive level of perception that comprises sensory processing and its interactions with attention. They characterized the visual perceptual mode by the form-resolving field, which was measured by the recognition of briefly presented letter pairs, one letter always at the center of gaze and the other in a lateral position. The plot of the correct recognition of the peripheral letter as a function of eccentricity is the form-resolving field (FRF). When the FRF was expressed numerically (Lorusso et al 2004), it classified 87% of the persons to be either dyslexic or typical reader correctly, as was verified by psychometric tests on over 350 subjects (Geiger and Lettvin 2000; Lorusso et al 2004). In addition, persons with different sub-types of dyslexia—whether dysphonetic, dyseidetic, and mixed according to Boder (1973), or L-type, P-type, and M-type according to Bakker (1979)—were found to have a similar wide visual perceptual model, suggesting that the wide perceptual mode is common to most dyslexics independently of the type of dyslexia (Lorusso et al 2004). As the FRF is a non-reading measure, it has the advantage of being independent of the language one is proficient in, but dependent on the direction of reading the language (Geiger et al 1992).

Studies that measured the FRF or its equivalent with direct optical display have shown that dyslexics had a significantly wider perceptual mode than typical readers (Dautrich 1993; Geiger and Lettvin 1987, 2000; Geiger et al 1992; Lorusso et al 2004; Perry et al 1989). However, other studies that measured the spatial width of perception (an equivalent measure to the FRF) with stimuli presented with CRT displays did not show significant differences between the groups (Goolkasian and King 1990; Klein et al 1990; Slaghuis et al 1992). The discrepancy between the latter studies and the previous ones is apparently due to the different methods of displaying the stimuli (Geiger and Lettvin 1998). It was shown that, for typical readers, the FRF was significantly wider when the stimuli were made of jagged letters (as they appear in the CRT display) compared with the FRF made with smooth-letter stimuli, although the letters were of the same contrast and width of stroke. However, the FRF of dyslexics was the same for both letter types (Geiger and Lettvin 1998). The widening of the FRF of typical readers with the jagged display apparently reduced the significance of the difference between the dyslexics and the typical readers (Geiger and Lettvin 1987; Geiger et al 1992; see also Schneps et al 2007).

It was suggested that the difference in the visual perceptual modes is accounted for by the difference in the distribution of lateral masking: little or no masking in the periphery, with some masking in and near the center of gaze for dyslexics, as opposed to strong lateral masking in the periphery with minimal masking in the center for typical readers. Differences in lateral masking between dyslexics and typical readers were suggested by Bouma and Legein (1977), and in crowding by Atkinson (1991) and Spinelli et al (2002). Supporting these suggestions were the findings that show that a regimen of practice designed for teaching a new perceptual model for reading (Geiger and Lettvin 1987) significantly improved reading in dyslexic children (Fahle and Luberichs 1995; Geiger et al 1994; Lorusso et al 2006) and adults (Geiger and Lettvin 2000) alike, while at the same time their FRFs narrowed to resemble those of typical readers (Geiger and Lettvin 2000; Geiger et al 1994). Furthermore, the dyslexics who practiced the regimen also improved on phonemic-awareness tests although they were not specifically trained for it (Lorusso et al 2006).

This wide perceptual mode could make reading difficult for dyslexics owing to their inability to perceive individual words without interference from the surrounding text (Geiger and Lettvin 2000). Related are studies that have pointed to problems dyslexics have in noise exclusion: visual perception in noisy environments (eg Sperling et al 2005) and in the auditory domain (Wright and Zecker 2004), particularly evident in backward masking (Ahissar et al 2000; Rosen and Manganari 2001; Wright et al 1997). In the light of the accumulating evidence on auditory processing deficits in dyslexics (eg McAnally and Stein 1996; Tallal 1980), temporal processing deficit (eg Farmer and Klein 1995), and attention deficit (eg Hari et al 1999) we were intrigued to explore whether the auditory deficit in dyslexics could have similar characteristics to that of the visual perceptual mode, especially after phoneme awareness—on written or oral tests—improved as the result of practice (of hand-eye coordination and reading with a window) that did not involve direct auditory training, which suggested possible multi-modal association (Lorusso et al 2006). This led us to explore whether these differences might reflect a more fundamental multi-modal processing. Specifically, we ask whether children with dyslexia differ also in the auditory perceptual mode, and, if so, what characterizes the differences. To address these issues, we measured the visual FRF and the auditory 'cocktail-party effect' in each of twenty-two Italian children: thirteen dyslexics and nine typical readers. Until now, the 'cocktail-party effect' has been used to measure the ability to recognize centrally presented stimuli in the presence of speech mask from the surrounding. We added to it the condition where the subjects were asked to report the central stimuli and the words perceived from the surrounding speech mask. This made it possible to measure the peripheral-to-central ratio of recognition, analogous to the visual FRF. Taken together, the two measures characterize the peripheral-to-central relation of visual and auditory perception for each individual subject.

2 Methods

All the participants were tested for their reading abilities, their spatial extent of visual recognition—the form-resolving field (FRF)—and their auditory perception of words presented centrally with or without the presence of peripheral masks of either speech or white noise—the 'cocktail-party effect'.

Both measurements were made with as little hardship as possible for the subjects. The FRF was measured in free sitting while ensuring fixation by the method of presentation. Free listening to loudspeakers (sound field) and not earphones (virtual listening) was preferred in the auditory measurements, as the loudspeaker mode resembles more the ecological listening conditions and is easier for the children. For the purpose of intelligibility, sound field and virtual listening are not significantly different (Hawley et al 1999).

2.1 *Subjects*

Thirteen dyslexic children (eleven males and two females) and nine typical readers (four males and five females) participated in the study. The diagnosis and the testing took place at the Scientific Institute 'Eugenio Medea'. The mean ages (range 9 – 13 years) of the two groups were 10.39 years for dyslexic children (standard deviation, SD = 2.19 years), and 10.99 years for typical readers (SD = 1.33 years) (t-test, $p > 0.8$).

All participants were native Italian speakers, with no obvious neurological and psychiatric disorders, and had intellectual abilities in the normal range. All subjects had either normal or corrected-to-normal vision, and intact auditory abilities. Dyslexic children were selected on the basis of the following criteria: (i) IQ higher than 85, assessed with either the WISC-R (Wechsler 1986) or the Test 'g' Culture Fair (Cattell and Cattell 1981); (ii) a performance at least two standard deviations below age-mean, in accuracy and/or speed, in a standardized test of text reading (Cornoldi et al 1986); otherwise, a performance at least one standard deviation below age-mean in text reading (Cornoldi et al 1986) with, in addition, performance of at least two standard deviations below age mean, in accuracy of speed, in a standardized reading test of lists of single words and/or non-words (Sartori et al 1995). Finally, (iii) none of the dyslexic children had a diagnosis of a specific language disorder.

Furthermore, all dyslexic children were tested on writing, under dictation, of single words, non-words, and sentences (Sartori et al 1995), and on phonological awareness tasks (Cossu et al 1988) ie phoneme elision (cancelling the first two phonemes of orally given words) and phoneme synthesis (integrating sequentially presented phonemes into words).

The scores of all the reading and writing tests are expressed, as shown in table 1, with normalized z scores, except for the scores of phonological awareness tasks that are expressed as total number of errors.

Typical readers were recruited from a local school, excluding children with mental retardation or emotional problems, developmental disorders, or other disabilities, as reported in the children's records. The children who arrived in the Institute were assessed with a short screening battery in order to exclude the presence of reading disorders, language comprehension disorders, or mental retardation. Specifically, typical readers were selected on the basis of the following criteria: (i) performance within one standard deviation from age mean, in both accuracy and speed, in the test of single-word reading (Sartori et al 1995); (ii) language comprehension in the normal range for the age, as assessed by the 'Comprehension of Syntactic Structures' test (Fabbro and Galli 2001); (iii) standard score superior or equal to eight in the Vocabulary and Block design WISC-R subtests (Wechsler 1986).

Table 1. The characteristics of the experimental and control groups (SD values in parentheses).

Group	Age	Words reading		Text reading		Non-word reading	
		speed	accuracy	speed	accuracy	speed	accuracy
Dyslexic readers ($n = 13$)	10.39 (2.19)	−3.49 (2.04)	−1.65 (1.44)	−1.81 (1.04)	−2.34 (1.16)	−2.35 (1.28)	−1.88 (1.80)
				Vocabulary	Block design	Language comprehension	
Typical readers ($n = 9$)	10.99 (1.33)	0.85 (0.89)	0.14 (0.72)	SS(2) = 12.7 (2.18)	SS = 12.7 (2.78)	Normal range	
p(1)	<0.8	<0.001	<0.01				

Group (continued)	Word writing	Non-word writing	Sentence writing	Phoneme	
	errors	errors	errors	elision errors	synthesis errors
Dyslexic readers ($n = 13$)	−1.26 (1.54)	0.37 (1.08)	−3.69 (2.84)	3.46 (3.76)	4.15 (3.48)

(1) p value according to the t-test.
(2) SS: standard score.

2.2 *Visual perception: FRF*

2.2.1 *Setup and stimuli.* The setup and stimuli of the visual FRF measurements were the same as those used by Lorusso et al (2004) and a copy of the one used by Geiger et al (1992, 1994). Three slide projectors, each equipped with a flat-field lens and an electrically activated shutter (Uniblitz—Vincent Ass.), back-projected images onto the same location on a white diffusing screen. The size of the slide projected on the screen was 48 cm × 32 cm, subtending 39 deg × 26 deg from 70 cm viewing distance. Each of the projectors gave a uniform luminance of 260 cd $\mathrm{m}^{-2} \pm 10\%$ across the screen. The first projector carried a slide with a central black fixation point; the second one carried the stimulus slide with two black letters on it; the third carried a blank 'eraser' slide (to erase the afterimage). A specially designed timer controlled electronically the opening and closing of the shutters, and the order and duration of presentations of the slides on the screen. The rise and fall times of the shutters were 3 ms each. Effective stimulus presentation durations (T_{eff}) as short as 3 ms were achieved by interspersing the opening and closing of the shutters in front of the slide projectors that carried the fixation, stimuli, and eraser slides. Luminance changes on the screen during these transitions were minimal ($< 10\%$). Stimulus duration was determined individually for each subject, and ranged between 3 and 18 ms (the change of duration was accompanied by a change in the effective contrast owing to integration time of the photoreceptors).

Each stimulus slide carried two uppercase letters, one always in the center at the location of the fixation point and the second in the periphery along the horizontal axis. The eccentricity of the peripheral letters varied from 2.5° to 12.5° from the fixation point, in 2.5° steps to the left and right. Twenty stimuli were presented at each eccentricity. In half of the slides, the peripheral letter appeared to the left of the central letter, while in the other half it appeared to the right, in random order. The two letters on each slide were different and were chosen from a fixed set of ten uppercase Helvetica-medium letters. Letter height subtended 35 min of arc, and letter contrast was 90%. Each letter appeared once at each of the eccentric positions, and twice in central position.

2.2.2 *Procedure for measuring the FRF.* The subjects sat at a distance of 70 cm from the screen in a dimly lit room. They were asked to gaze at the fixation point. After a verbal warning, the stimulus slide was projected (replacing the fixation-point slide) followed by the blank eraser slide that was projected for 2.5 s, after which the fixation point was presented again to start a new cycle. The subject was requested to name the two letters specifying their locations. Both letters were part of the stimuli, although the letter at the center served also to control fixation and attention. After responding to all the stimuli, the average scores for each location was calculated and the FRF plot of correct identification of the peripheral letters as a function of eccentricity was made. The score of correct identification of the central letters was usually given numerically but not shown here as it was about 100% for all the subjects. The random order of the side of presentation of the peripheral letters prevented anticipatory bias of gaze to either side of the fixation point. That, together with 100% (or close to it) recognition of the central letter was considered as confirming that fixation was kept in the center of the screen and attention was kept to the task. Furthermore, the experimenter visually controlled the subjects' fixation.

The stimulus duration (which we name T_{eff} for 'effective duration') was determined individually for each subject before the actual measurement. The chosen duration was the time at which the subject's recognition was just 100% at 2.5°, and below at greater eccentricities. This normalization procedure prevents saturation effects and by this makes it possible to determine the relative peripheral-to-near-central ratio of recognition at the optimal stimulus duration for each individual. The duration of stimulus presentation for each subject was kept constant throughout the actual FRF measurement.

The blank eraser was chosen in order to minimize the disadvantage dyslexics have because of backward masking of structured masks (eg Di Lollo et al 1983). Owing to the normalization, and in part also to the choice of the blank eraser, stimulus durations were shorter than would have been with structured erasers.

2.3 *Auditory perception: The cocktail-party effect*

2.3.1 *Central stimuli and setup.* The central stimuli were single Italian words, 15 names of persons and 15 names of letters spoken by a woman native speaker of the Italian language. They were delivered by a central loudspeaker placed in front of the subject at a distance of 110 cm and approximately at the subject's ear height. The overall sound level (rms power) of the central stimuli was set to a comfortable listening level of approximately 56 – 62 dB (SPL) at the subject's position.

2.3.2 *Masks.* There were two different masking conditions: speech and white-noise masks. Four peripherally positioned loudspeakers delivered the masks, two on each side of the central loudspeaker. All the loudspeakers were at a distance of 110 cm from the subject, and placed in a semi-circular arrangement with distances of 60 cm between the speakers, ie with eccentricities of 31.5° apart. The conversation of three pairs of Italian women on mundane topics served as the speech mask. It was delivered from the four peripheral loudspeakers, giving the impression of multi-location speakers. The white-noise mask was delivered from the same loudspeakers with the same arrangement.

At the subject's position, the overall sound level (rms power) coming from the four peripheral loudspeakers together was set to approximately 66 – 72 dB (SPL) (with equal sound level from each of the peripheral loudspeakers). The overall sound level (rms power), at the subject's position (from the speakers delivering the masks and the central stimuli together) was 69 – 74 dB (SPL). A computer monitor was placed just below the central loudspeaker at a distance of 65 cm in front of the subject to display a small fixation cross.

The speech of the central stimuli as well as the speech-mask conversations were first digitally recorded in a studio and later transferred to the computer. The stimuli and each pairs' conversation were recorded separately. The speech was filtered with a low-pass digital Butterworth filter with a cutoff of 4000 Hz. Each word of the central stimuli was saved in a separate file. The conversation of each talking pair was cut into 5-s-long pieces and saved in separate files. All the audio pieces in the files (both stimuli and mask) were normalized to the same rms level.

For each of the speech-mask pieces a compatible piece of white-noise signal mask was generated with the same length filtered in the same way as the speech mask (low pass 4000 Hz) and then shaped in amplitude with the same envelope as the corresponding speech-mask piece. All the pieces obtained were saved in the computer as separate files. In the masked conditions, the central stimuli were delivered during the delivery of the speech (or white-noise) mask. Every central-stimulus utterance was coupled to three pieces of speech mask (or white noise). For each particular central stimulus the same three conversation pieces (or corresponding white-noise fragments) were delivered from the same configuration of loudspeakers. For each central stimulus three different mask pieces were chosen.

A computer equipped with three stereo sound cards with the appropriate digital-to-analog conversion hardware drove the loudspeakers. Software was prepared to deliver both the stimuli and masking controlling the timing relation between the central stimulus, the masks, and their levels. This was achieved by addressing one of the central stimuli files and three of the masking ones for each event. (The computer used for speech acquisition, the stimuli, and masks delivery had a Pentium III 500 MHz processor with 512 MB RAM and 30 GB hard disk.)

2.3.3 *Procedure.* The subject was seated in an irregular small quiet room in which the head of the subject was at equal distance (130 cm) from the walls on the sides (see Shinn-Cunningham et al 2005). The walls of the room were coated with soft cloth and in parts were covered with egg-trays made of paper. The noisy equipments were placed outside the room. Every auditory measurement comprised four successive parts, in all of which the subject's task was to report verbally what he/she perceived from the central stimuli. In part 1 only the central stimuli were delivered from the loudspeaker at the center. In part 2 each central stimulus was embedded in the speech mask which was delivered from the four peripheral loudspeakers. Part 3 was similar to part 2 in its arrangement except that the white-noise mask replaced the speech mask. We are aware that there is a difference in recognizing speech embedded in informational or energetic maskers (at signal-to-noise ratios of 0 to 10 dB between the stimuli and the maskers) as described by Brungart (2001). Part 4 was similar in presentation to part 2 regarding the delivery of the stimuli and the speech mask. However, in this part the subject's task was first to report the words perceived from the central stimuli and then to report also words perceived from the surrounding speech mask, so that the speech mask was part of the stimuli.

In each part the central stimuli were presented in two separate blocks: one with 15 letter names and the other with 15 person names. The order of presentation within each block was different for each part. The central stimuli and central stimuli – mask combinations were identical for all the subjects.

In all the four parts the experimenter initiated the stimulus cycle: first, a fixation cross appeared on the screen and stayed there for 5 s. The start of the central stimulus was 1, 1.5, 2, 2.5, or 3 s (randomly chosen) after the onset of the fixation cross. After the presentation of the stimulus, the subject was asked to report verbally what he/she had perceived. The experimenter noted the report and a new cycle followed. In parts 2, 3, and 4 the cycles started with the display of the fixation cross coinciding with the start of the delivery of the mask. The onset of the central stimulus was delayed in the same way as described above. Since the duration of central stimuli was short, the masks were delivered for just 1 s after the end of the stimuli. Every measurement started with part 1 while the order of presenting parts 2, 3, and 4 was randomized across subjects.

3 Results

3.1 *Visual perception—the FRF*

The FRF plots are shown in figure 1. The average FRF of the dyslexics is wider than that of typical readers. Being interested in the relations between peripheral and near-central perception, we calculated the periphery-to-near-central ratio of correct recognition—the $C_{1/2}$ criterion—for every subject. It was calculated by taking the ratio of correct recognition in the peripheral eccentricities (adding the percent correct recognition scores at -12.5°, -10°, 10°, and 12.5°) and dividing that sum by the sum of correct recognition near the center (at -2.5° and 2.5°). Higher values point to better recognition in the periphery (this criterion is the inverse value of C_2 given in Lorusso et al 2004). The average $C_{1/2}$ values for each group are shown in figure 2.

The ratio for dyslexics is significantly higher than that for typical readers (*t*-test, $p < 0.02$). As the direction of reading is considered to be the determinant side (see Geiger et al 1992; Lorusso et al 2004), we also give the values for $C_{1/2\mathrm{R}}$, which is the value of $C_{1/2}$ calculated for the right visual field only (also shown in figure 2 on the right). Indeed, an ANOVA with group, side, and eccentricity as factors showed significant main effects for side ($F = 35.11$, $p < 0.001$) and eccentricity ($F = 301.339$, $p < 0.001$), with no significant effects for group ($F = 0.108, p > 0.50$). More importantly, a significant interaction emerged between side and eccentricity ($F = 3.059$, $p = 0.04$), and between eccentricity and group ($F = 8.518$, $p < 0.001$). The effect of side depends on recognition rates being lower on the right side, and especially so at 5°, 10°, and 12.5° (interaction with eccentricity). The interaction of group with eccentricity depends on the recognition of dyslexics being significantly lower than that of controls at 5° ($F = 5.308$, $p = 0.032$) and significantly higher than that of controls at 12.5° ($F = 7.756$, $p = 0.012$).

The average stimulus duration (T_{eff}) for dyslexics was 8.6 ms which is significantly longer ($p < 0.001$) than that of typical readers (4 ms). The recognition rate of dyslexics being significantly lower than that of controls at 5° but significantly higher than that of controls at 12.5° suggests that the longer T_{eff} did not actually bring advantage to dyslexics performance, but that its effect, if any, varies with eccentricity. Furthermore, the difference in $C_{1/2}$ is still significant when T_{eff} is taken as a covariate ($F = 4.436$, $p = 0.049$).

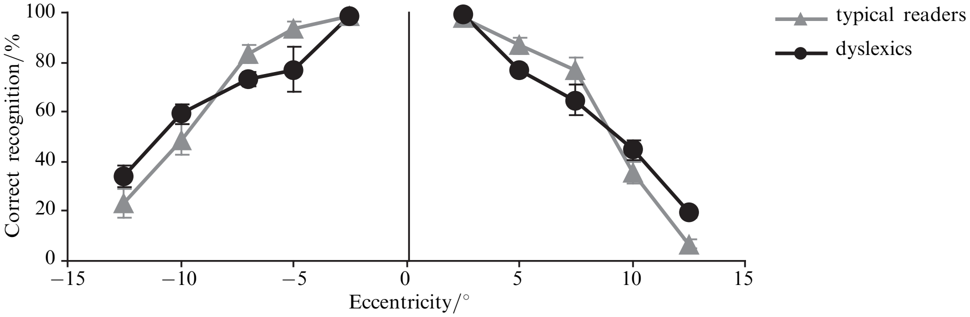

Figure 1. The average form-resolving field (FRF) of thirteen dyslexic and nine typical readers.

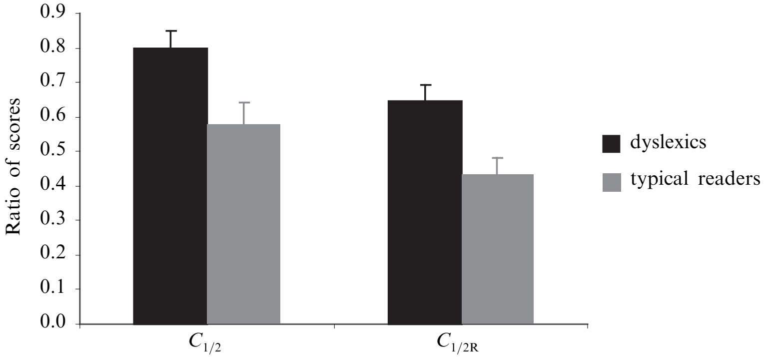

Figure 2. The ratios of the peripheral to near-central recognition scores: (left) for both sides; in the periphery [at $-12.5° + (-10°) + 10° + 12.5°$] divided by the recognition score near central locations (at $-2.5° + 2.5°$) which is the $C_{1/2}$ criterion, and (right) the same on the right side only. The bars denote ±1 SE.

3.2 *Auditory perception—the cocktail-party effect*

The recognition of the central stimuli alone (part 1)—single words delivered from the central loudspeaker—was similar for both groups ($p > 0.5$) (depicted in the leftmost columns of figure 3a). However, in the presence of speech mask (part 2) the correct recognition of the central stimuli fell off sharply for both groups (figure 3a), with the level of recognition by dyslexics being significantly lower than that by typical readers ($p < 0.02$). In the presence of white-noise mask (part 3), the recognition of the central

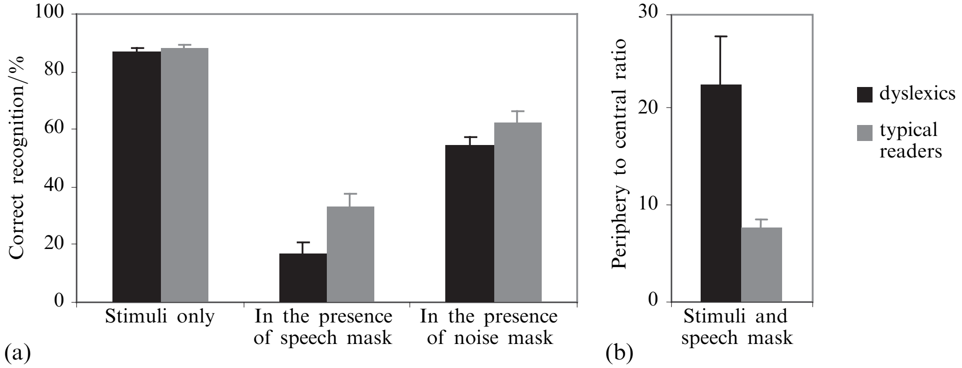

Figure 3. The cocktail-party effect. (a) The recognition scores of the central stimuli by dyslexics and typical readers: in the condition of stimuli alone (part 1); in the presence of speech mask (part 2); in the presence of white-noise mask (part 3). (b) The ratio of the number of words recognized from the surrounding speech mask to the number of words recognized from the central stimuli in the presence of speech mask (part 4.).

stimuli by both groups was compromised by the mask but to a lesser degree than by the speech mask (figure 3a), and the difference between the groups was not significant ($p > 0.3$). Figure 3b depicts the subjects' average ratio of the number of words recognized from the surrounding speech mask to the number of words recognized from the central stimuli (part 4), for each group separately. An ANOVA performed on the data with group and condition (part 2 versus part 3) as factors showed significant main effects of group ($F_{1,20} = 5.63$, $p = 0.028$) and condition ($F_{2,40} = 283.66$, $p < 0.001$), and a significant group × condition interaction ($F_{2,40} = 4.98$, $p = 0.012$).

This ratio for dyslexics is significantly higher ($p < 0.05$) than that for typical readers. However, the average number of words recognized by each subject from the speech mask was similar for dyslexics (86.7) and typical readers (88.0) (from a total of 899 words uttered in the mask). Thus the difference in the ratio of periphery-to-center recognition seems to emanate from the difference of recognition of the central stimuli. This part is most similar to the visual FRF measure where in both domains stimuli were presented in the center and the periphery at the same time.

3.3 *Auditory and visual perception considered together*

One goal of this study was to enquire whether the wider and more diffuse perceptual mode in dyslexics is general for the two sensory modalities. That is, would a dyslexic have both wider and more diffuse visual and auditory perceptual modes?

Each point in the scatter diagram (figure 4) represents an individual subject where the y-coordinate depicts the visual dimension by units of the $C_{1/2R}$ ratio and the x-coordinate depicts the peripheral-to-central ratio of correct recognition of words in the auditory dimension.

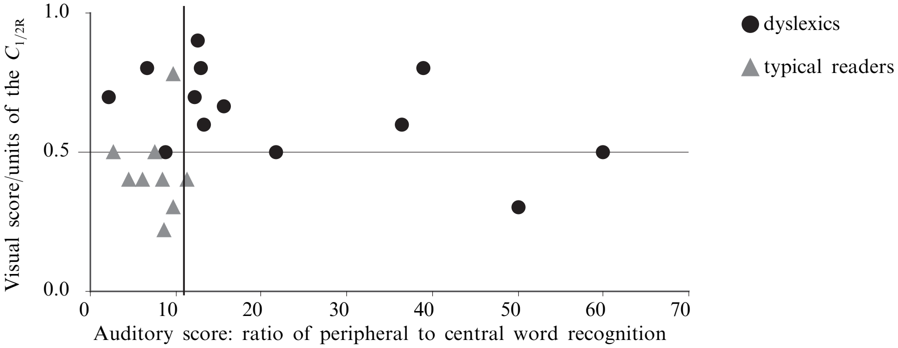

Figure 4. Each data point represents one individual's scores for the visual ($C_{1/2R}$) and the auditory peripheral-to-central ratios. The vertical line (at 10.2) is 1.65 SD away from the calculated auditory threshold of the two-dimensional average for typical readers and the horizontal line (at 0.5) is that for the visual modality.

The two-dimensional means of each group are significantly different ($p < 0.001$) as calculated by Wilk's λ. That is to say that on average dyslexics and typical readers are significantly different in perception in both the visual and the auditory dimensions. To estimate the prevalence of the wider perceptual mode in both domains for each individual dyslexic we established a threshold of deviation for the typical readers, separately for the auditory and for the visual domains. We did that following two methods: the first resembles that of Ramus et al (2003) where the threshold line was set to 1.65 SD of the mean above the mean of the typical readers in each dimension; in the second method—that gave similar results—the threshold lines were obtained by fitting a Gaussian for each data point (in each sensory modality) and then constructing a distribution for each group. We took the value where the lines of the distributions crossed as the threshold in each dimension. The values we got were 0.5 for the visual dimension (see also Lorusso et al 2004) and 10.2 for the auditory dimension (see figure 4). The values for all the dyslexics are equal or larger than the threshold lines in at least one modality and for nine dyslexics (69.2%) in both modalities.

4 Discussion

The measurements presented here show a wide spatial distribution of visual perception of letters and of auditory perception of words in the presence of speech mask in dyslexics, while typical readers have a narrower distribution in both modalities. The width of perception is determined by the peripheral-to-near-central ratio of recognition of letters in vision and of words in audition. Common to both modalities is that differences between the groups were demonstrated with stimuli characterized as objects, relating to a higher integrative level of perceptual processing, ie letters (forms) in visual perception and words in auditory perception. As was demonstrated more pointedly in the auditory domain, only in the presence of speech masking (informational masking—eg Brungart 2001) was it possible to demonstrate significant differences in the perception of stimuli between dyslexics and typical readers. By contrast, when the stimuli were masked with white noise (energetic masking), or not masked at all, the perception of the stimuli by the groups showed differences but not significant ones. The stimuli were high-contrast large letters in vision and moderately loud clearly spoken single words in audition. For such visual stimuli the responses to contrast, illumination, color, resolution, and orientation of simple attributes are usually unimpaired in the dyslexic population (eg Boden and Giaschi 2007). Moreover, the data show that auditory responses to single isolated words are similar for both groups. This suggests that the differences found in perception between dyslexics and typical readers could be attributed to higher integrated processing levels, somewhere between the pre-cognitive sensory processing and cognition—at the perceptual mode level. This might suggest that there are many contributing factors to the differences, possibly subtle differences in early sensory processing and other differences along the hierarchical path of processing.

4.1 *Visual perceptual modes*

The visual perceptual mode of dyslexics is significantly wider than that of typical readers as measured with the FRF, in agreement with earlier studies (Dautrich 1993; Geiger and Lettvin 1987, 2000; Geiger et al 1992; Lorusso et al 2004; Perry et al 1989). These studies had in common stimuli that were presented with direct optical displays. As mentioned before, in other studies of the spatial width of perception (an equivalent measure to the FRF) with stimuli presented with CRT displays no significant differences between the groups have been found (Goolkasian and King 1990; Klein et al 1990; Slaghuis et al 1992) for reasons mentioned in section 1. Individual reports by dyslexics also support the notion of wide visual perceptual mode. They often say that they “see almost as clearly much of the text surrounding the word to be read as the word itself”. In addition, word-by-word presentation of text was also shown to improve reading by dyslexics (Hill and Lovegrove 1993). These findings suggest that the text surrounding a word to be read perturbs dyslexics in their attempt to read that word and reading in general.

The duration of presentation of the stimuli was determined individually for each subject by normalizing recognition level to the letter presented nearest to the center of gaze. The average presentation duration for dyslexics was 8.6 ms, significantly longer than that for typical readers (4 ms). This suggests that letter recognition near the center of gaze is more difficult for dyslexics than for typical readers, while, as seen from the FRF, letter recognition scores are higher for dyslexics in the periphery. Similar results were obtained for dyslexic adults also when measurements were made without the normalization procedure (Perry et al 1989). That is, visual perception of letters by dyslexics is not only spatially wider than by typical readers but is also more diffuse in terms of discrimination. In other words, dyslexics have a wider and more diffuse visual perceptual mode than typical readers; this is similar to previous results shown in adults (Geiger and Lettvin 1987; Geiger et al 1992) and in children (Geiger et al 1994; Lorusso et al 2004).

The differences in the FRF between dyslexics and typical readers are similar to the differences in lateral masking that was previously measured with strings of letters at different eccentricities. Dyslexics have stronger lateral masking/crowding at and near the center of gaze than typical readers and weaker in the periphery (Geiger and Lettvin 1987; Geiger et al 1992), ie the distribution of the effect of lateral masking is wide and diffuse for dyslexics and narrow and pointed for typical readers. As the plot of the FRF resembles the distribution of lateral masking, the FRF has been considered to be also a measure of the distribution of lateral masking across the visual field (Geiger et al 1992). That could be justified on the ground that, in each stimulus of the FRF, two letters are simultaneously presented with their percept interacting, and that letter parts laterally mask each other (Geiger and Lettvin 1986; Liu et al 2007; Martelli et al 2005). In addition, stronger lateral masking/crowding in and near the center of gaze was shown in dyslexic children (eg Atkinson et al 1988; Bouma and Legein 1977; Spinelli et al 2002; but see Bouma and Legein 1980). There is a large body of psychophysical experimentation with lateral masking (or crowding or clutter) and attempts to explain the percept (eg Bouma 1970; Pelli et al 2004). Recently, electrophysiological recordings in primates were made to study the effect of clutter, that is, compare the responses of a neuron to a single object with its responses to the same object while surrounded by other objects.

Electrophysiological studies show that neurons in the anterior inferotemporal (IT) cortex—which is the highest stage of the ventral ('what') stream (Ungerleider and Mishkin 1982)—are selective for complex objects (eg Logothetis and Sheinberg 1996). Other studies have shown simple shape selectivity also in the posterior parietal cortex that is in the 'where' (dorsal) stream (Sereno and Maunsell 1998). A recent comparison of shape selectivity between the streams suggested more complex shape selectivity in IT cortex than in the lateral intraparietal area in the dorsal stream (Lehky and Sereno 2007). Recordings from IT cortex in primates have shown that the presence of limited clutter conditions reduced the responses to target objects on their own to the average-like responses of its constituent objects in isolation (eg Zoccolan et al 2005). In a later study of IT neurons the relations between shape selectivity and tolerance to variation of appearance including clutter were measured and IT neurons were found to be an inhomogeneous population with a clear trade-off between the neuron's selectivity to the shape of objects and tolerance to shape variation and clutter. The neurons tolerant to clutter had poor object selectivity while neurons highly selective to objects had low tolerance to clutter (Zoccolan et al 2007). These results were interpreted in terms of a hierarchical feedforward computational model of object recognition in the ventral pathway (Riesenhuber and Poggio 1999; Serre et al 2005, 2007) in which neural tuning is multi-dimensional in neural input space that deterministically computes responses from the afferent neurons. In the model, more highly selective neural responses are the result of narrow multi-dimensional tuning, while wider tuning results in more tolerance to appearance variations.

This kind of trade-off is similar to what we observe in the difference between dyslexics and typical readers. We suggest that dyslexics have wider neural tuning which results in increased tolerance to lateral masking/clutter and reduced selectivity, manifested by reduced recognition at and near the center of gaze, along with reduced lateral masking in the periphery. On the other hand, typical readers have narrower neuronal tuning which results in higher selectivity and reduced tolerance to clutter, seen by better recognition at and near the center of gaze and stronger lateral masking/clutter in the periphery.

In addition, electrophysiological recordings in the prefrontal and posterior parietal cortices suggest that bottom – up attention arises from the sensory cortex while top –down attention arises from the frontal cortex (Buschman and Miller 2007). In general, both stimulus-driven and voluntary attention are incorporated and in most cases enhance object recognition (for reviews see Desimone and Duncan 1995; Hochstein and Ahissar 2002).

As the perceptual mode of dyslexics is spatially wider (as measured by the FRF), this also implies differences in spatial and selective attention mechanisms beside and in addition to neural selectivity suggested above. Recent studies have shown that spatio-temporal and spatial attentional deficits characterize dyslexics (Brannan and Williams 1987; Buchholz and McKone 2004; Cestnick and Coltheart 1999; Facoetti et al 2005; Roach and Hogben 2004, 2007). The differences in attention that dyslexics show were connected to the magnocellular deficit theory of dyslexia (Hari and Renvall 2001; Stein and Walsh 1997). Our discussion above was centered on the ventral streams; however, this does not exclude the possibility that similar processes are present in the dorsal stream (eg Friedman-Hill et al 2003; Saalmann et al 2007) and interact with the ventral stream.

Support for the suggestion of the combined effects of wider neural tuning and wider spatial attention for dyslexics could come from studies of treating dyslexia (Fahle and Luberichs 1995; Geiger and Lettvin 2000; Geiger et al 1994; Lorusso et al 2006). These studies have shown that, relying on plasticity, a regimen of practice comprised of small-scale hand – eye coordination tasks and reading with a window mask significantly improved reading while narrowing the FRF in most cases. This combined regimen addresses narrowing of attention by visual—motor cross-modal adaptation through active practice (Held and Gottlieb 1958; Held and Hein 1958; Welch et al 1998) and sharpening the neural tuning for recognition by perceptual learning processing (Fahle 2005; Gilbert et al 2001; Nazir et al 2004; Seitz and Watanabe 2005) that results in an improvement in the reading ability of dyslexics.

4.2 *Auditory perceptual modes*

Recognition of the words delivered by the central stimuli alone was comparable for dyslexics and typical readers. However, in the presence of a surrounding speech mask the recognition of the central stimuli was reduced for all subjects, with that of dyslexics to a significantly greater extent than that of typical readers. It is most likely that the presence of the surrounding speech mask is amplifying the dyslexics' disadvantage which, as suggested, is a deficit in phoneme perception due to auditory temporal perception (Merzenich et al 1996; Tallal 1980; Tallal et al 1996) and selective impairment in frequency discrimination, in spite of normal hearing sensitivity and binaural masking level (Amitay et al 2002; Hari et al 1999; Hill et al 1999; but see McAnally and Stein 1996). On the other hand, the recognition of words from the surrounding speech mask by dyslexics was as good as that of typical readers, suggesting intact perception of the surrounding speech.

In order to disentangle mixtures of sounds, the auditory apparatus segregates the sounds into auditory streams (Bergman 1978) that depend on amplitude and frequency modulation and frequency separation for grouping cues (Bergman 1990). Stream formation does not require attention, as stream segregation occurs also outside the focus of attention (Sussman et al 2007). In addition, spatial separation aids the listener by providing binaural cues (Bronkhorst 2000) and their interactions (Hawley et al 2004) to segregate sound sources, especially so with informational masking (Arbogast et al 2002).

Dyslexics were as able as typical readers to activate the processes described above for recognizing words in the surrounding speech mask. That is, dyslexics and typical readers were equally able to perceive words in the surrounding speech mask, although these words were also masked by other words from the surrounding speech mask. However, for the central stimuli the differential binaural cues were unavailable for recognition.

Hence, the subjects had to rely on the remaining cues for intelligibility which were strongly reduced by the speech mask (Hawley et al 2004). This was true for all the subjects, but the dyslexics were more affected, as their recognition of the central stimuli was significantly poorer in the presence of the speech mask. The surrounding speech mask and the lack of binaural differential cues appear to have amplified the deficits of reduced temporal discrimination and frequency discrimination attributed to dyslexics. Put together, dyslexics have reduced selectivity at the center, compared with typical readers, together with adequate recognition of words in the surrounding speech mask, resulting in significantly higher ratio of peripheral-to-central word recognition.

The differences in the auditory/language perception between dyslexics and typical readers seem to have similar characteristics to those found in visual perception. If the difference between dyslexics and typical readers is in the visual perceptual modes, it is compelling to suggest that the difference between the groups is also in the auditory perceptual modes (see also Shinn-Cunningham 2008).

The recognition rate of the central stimuli in the presence of a surrounding white-noise mask was lower for all subjects and somewhat lower for dyslexics; however, it was significantly lower than that of typical readers in the presence of surrounding speech masks. That is, the difference between the groups is significantly greater in the presence of informational masking than in the presence of energetic masking, suggesting that the difference lies in a higher integrative, pre-cognitive level.

Aspects of the auditory mode are similar in character to the description of IT neurons in the visual cortex that suggest a trade-off between selectivity and tolerance to clutter (Zoccolan et al 2007), where the reduced selectivity by dyslexics reflects wider multi-dimensional neural tuning with increased tolerance to clutter. That, combined with wider spatial attention, describes the visual perceptual mode. We propose that similarly, in the auditory domain, dyslexics have a wider neural tuning with greater tolerance for clutter in the periphery combined with wider spatial attention, ie their auditory perceptual mode is wider and more diffuse.

As in the visual domain, the difference in the auditory domain between the dyslexics and typical readers is characterized by the interactions between feedforward sensory processing and spatial attention. Recognition of the words in the speech mask by the dyslexics suggests that the reduced recognition of the central stimuli is not cognitive but pre-cognitive. The higher 'signal-to-noise' ratio required by dyslexics as a consequence of the 'processing efficiency' deficit suggested by Hartley and Moore (2002) might well be related to wider multi-dimensional neuronal tuning as suggested for vision.

Recent electrophysiological studies on the A1 of ferrets suggested rapid dynamic receptive-field plasticity and adaptation to changing acoustic saliences that might be driven by top – down attention (Fritz et al 2007). In addition, cortical plasticity of the auditory system of mammals is specific to the salient inputs in the sensory environment or when it is associated with electrical stimulation of the basal forebrain. It has also been shown that sensory experience leads to changes of the topographical organization of the auditory cortex, receptive field size, and other temporal characteristics of the auditory cortex (Kilgard et al 2002). More specifically, one general property of plasticity is neural tuning, as driven by experience, in the developing animal/human and the adult. An important aspect of that process depends on the salience of the experienced signal. It is suggested that low salience (low fidelity) results in broadly tuned and less selective neural substrate (Merzenich 2003).

As our aim was to measure the spatial peripheral-to-central recognition ratio, we did not test the condition where the speech mask and the central stimuli were coincidental in the center. It is reasonable to assume that in this condition the recognition of the central stimuli and the speech mask would have been reduced (see Hawley et al 1999). Adding this condition would have made the testing period too long.

4.3 *Multi-sensory perceptual modes*

The detection of a brief visual or auditory signal rapidly followed by noise (backward masking) is impaired by dyslexic children (eg Di Lollo et al 1983; Montgomery et al 2005). Moreover, auditory backward masking requires not only non-word reading abilities but also phonological skills (Montgomery et al 2005). Both temporal (Di Lollo et al 1983; Montgomery et al 2005) and spatial (eg Sperling et al 2005) processing windows in which noise interferes with the signal appear to be broader in dyslexics than in typically reading children. This has been referred to as a "perceptual noise exclusion" deficit (Sperling et al 2005). Ziegler and colleagues (2005) showed that children with specific language impairment (SLI) have poorer-than-normal phoneme identification only when measured in ecologically valid conditions of stationary or fluctuating masking noise. In addition, speech identification in noise was strongly correlated with reading skills of SLI children. We suggest that a possible contributor to the multi-sensory wider and more diffuse perceptual mode in dyslexics could be in part their sluggish engagement of spatial attention (see Hari and Renvall 2001). Visual and auditory selection mechanisms (ie selective attention) operating on graphemes and phonemes appear to be basic components of the phonological assembly process. We suggest that the engagement deficit specifically impairs grapheme parsing and speech segmentation in dyslexic children (Facoetti et al 2006).

Although similarities between the visual and auditory mode were demonstrated, it is important to note that, as expected, the results of the auditory and visual recognition were not identical owing to differences in stimulus presentation. Are the perceptual differences seen in dyslexics modality-specific? Dyslexics and typical readers differ significantly in both visual and auditory perceptual modes, as well as in the two-dimensional mean of both modalities. All dyslexics have a wider perceptual mode in at least one modality and 69% of them in both modalities. This suggests that the wide and diffuse multi-sensory perceptual mode is common to dyslexics. Although this study included only twenty-two subjects, previous studies on a much larger number of subjects came to similar results in the visual domain (Geiger and Lettvin 2000; Lorusso et al 2004), also showing that the wide perceptual mode is common to various subtypes of dyslexia (Lorusso et al 2004). We can conclude that the wide perceptual mode is common to both the visual and the auditory domain. This suggests at least two possibilities: either there is a general perceptual mode that subordinates each modality, or each modality is separate from the others, and the similarity between the perceptual modes is due to similar requirements of the tasks and the congruency of features involved in accomplishing the tasks.

That the dyslexics and typical readers demonstrate similar differences in the characteristics and functions in vision and audition might suggest that the origin of these differences is common in these modalities. The sluggish attentional shifting of dyslexics (Facoetti et al 2003b, 2005; Hari and Renvall 2001) in both modalities is a compelling indication of a generalized factor in perceptual modes. However, modulation of the neural process and of neural tuning by attention is not sufficient if the neural tuning cannot be narrowed further. It appears that attention alone is not sufficient to change it (Vidyasagar 2005). Furthermore, only 69% of dyslexics have wide perceptual modes in both modalities. This might favor the conclusion that each modality is characterized by its own perceptual mode. The following questions remain open: what is the base of wider neural tuning with reduced selectivity and higher tolerance for clutter that is common to all dyslexics? And what are the conditions for the activation of anatomical and physiological multi-sensory integration (eg Ghazanfar et al 2005)? Important also to note is that the consequences of wider multi-sensory perceptual modes have larger implications than for reading alone. It was suggested that global visual – spatial processing or 'holistic inspection' is linked to talent (von Karolyi et al 2003; see Schneps et al 2007 for a recent review).

To conclude, our evidence suggests that dyslexics differ from typical readers in having a wider and more diffuse visual perceptual mode which is characterized by reduced selectivity in the near-central part of the visual field and tolerance to lateral-masking/crowding/clutter in the periphery. Furthermore, results from the cocktail-party effect show similar differences between dyslexics and typical readers in the auditory perceptual mode: reduced selectivity in the center in the presence of surrounding speech masks, and tolerance to the mask in the surrounding. We suggest that the consistent differences in both modalities may be explained by wider multi-dimensional neural tuning that interacts with sluggish spatial attention. Improvements in performance following interventions that lead to better focusing of attention and narrowing of the multi-dimensional neural tuning by practice, as shown in the visual domain (eg Geiger et al 1994; Lorusso et al 2006) and in the auditory domain (Merzenich et al 1996; Tallal et al 1996) support this claim and provide ways for remediation.

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