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An auditory temporal processing deficit in children with dyslexia?

Mieke Van Ingelghem, Bart Boets,

Astrid van Wieringen, Patrick Onghena, Pol Ghesquière,

Erik Vandenbussche† and Jan Wouters

Introduction

Developmental dyslexia is characterised by serious reading and spelling problems that are persistent and resistant to the usual didactic measures and remedial efforts (Gersons-Wolfensberger & Ruijssenaars, 1997). However, a lot of research has shown that problems of individuals with dyslexia extend beyond the domain of written language and affect their performance on tasks that require phonological processing (see Snowling, 2000 for a review). It is therefore widely acknowledged that in cognitive terms, individuals with dyslexia have a phonological deficit, which is causal to their reading and spelling difficulties.

Investigation into the underlying neurological dysfunction of dyslexia suggests these phonological problems result from a more fundamental deficit in the basic perceptual mechanisms responsible for auditory temporal processing. This hypothesis was put forward by Tallal (1980), who found that children with dyslexia, in comparison to normal readers, were impaired in discriminating and sequencing acoustic stimuli that are brief and occur in rapid succession. This impairment was supposed to apply to both non-linguistic and linguistic auditory stimuli and have particular impact on the perception of syllables containing stop

consonants, such as /ba/ and /da/ (Tallal, Miller & Fitch, 1993). Perception of these syllables critically depends on accurate detection of the rapid frequency changes in the first milliseconds of voicing (formant transitions). Inaccurate detection of these formant transitions inevitably interferes with the identification of the phonological cues that are typical for spoken language. To summarise, the theory of Tallal and colleagues states that individuals with dyslexia have a deficit in perceiving brief duration and rapidly occurring temporal cues, i.e. within a time frame of milliseconds. This basic perceptual deficit causes a problem for the accurate detection of the rapid acoustical changes in speech. Consequently, the speech-perception problem causes a cascade of effects, starting with the disruption of normal development of the phonological system and resulting in problems learning to read and to spell (see also studies of Nagarajan et al., 1999; Wright et al., 1997).

Studdert-Kennedy and Mody (1995) challenge this theory because of its implicit assumption that rapid sequences of brief stimuli are acoustically equivalent to the integral spectral sweeps of formant transitions. According to these authors, stimulus processing is temporal only when the defining features of the stimuli are changing in time (later called "dynamic stimuli", see Talcott et al., 2000; Talcott & Witton, 2002; Witton, Stein, Stoodley, Rosner & Talcott, 2002). Besides their criticism on Tallal's "rapid and brief" operationalization of temporal processing, Studdert-Kennedy and Mody also argue that the observed phonological impairments in dyslexics are in origin speech-specific and cannot be attributed to a more general lower-level auditory deficit. Therefore, dyslexics' difficulties to distinguish stop-vowel syllables do not unquestionably reflect an auditory temporal processing deficit, meaning a deficit in the perception of rapid spectral changes (Mody, Studdert-Kennedy & Brady, 1997; see also Nittrouer, 1999).

Moreover, McAnally and Stein (1996) found that adults with dyslexia were not significantly different from normal readers for detection of a temporal gap in broadband noise and detection of a tone in a diotic noise masker when the tone was in phase at two ears. On the contrary, significant group differences were found for a frequency discrimination task and the tone-in-noise detection task when the tone was presented with opposite phase at two ears. This may indicate that the dyslexics' neural coding of stimulus onsets and offsets was normal, but that they were impaired in their ability to generate or exploit neural discharges phase-locked to the fine structure of acoustic stimuli. Data consistent with these findings were reported by Baldeweg, Richardson, Watkins, Foale & Gruzilier (1999), Dougherty, Cynader, Bjornson, Edgell & Giaschi (1998) and Schulte-Körne, Deimel, Bartling, & Remschmidt (1998). Also Talcott et al., (2002) reported similar observations from a large-scale primary

school study in which auditory frequency resolution differed between groups of children with different literacy skills.

The latter evidence and Studdert-Kennedy and Mody's criticism on Tallal's theory have lead to studies that investigate auditory temporal processing in dyslexia using stimuli that specifically change in time. In these studies, in which adult samples were used, dyslexics were found to be less sensitive than controls to amplitude modulation (AM) (McAnally & Stein, 1997; Menell, McAnally & Stein, 1999) and frequency modulation (FM) (e.g. Stein & McAnally, 1995). A remarkable study in this context is from Witton, Talcott, Hansen, Richardson, Griffiths et al. (1998) who have shown that adults with dyslexia were less sensitive than controls to 2Hz and 40Hz FM, but not to 240 Hz FM. In the first two cases detection is achieved by tracking the actual frequency change of the carrier over time (= a temporal process), whereas in the third case, detection is achieved by detecting a pair of extra spectral components separated from the carrier frequency by the modulating frequency (= a spectral process). In addition, Witton et al., (1998) found that sensitivity to 2 and 40 Hz FM, for both dyslexics and controls, highly correlated with their measure of phonological decoding skill. This relationship between FM sensitivity and phonological ability was also demonstrated by Talcott et al. (1999, 2000) in a random group of children.

These studies again point to an auditory temporal processing deficit as a possible cause of dyslexics' phonological problems. Accurate tracking of amplitude and frequency changes is exactly what is needed for the perception of speech, which is characterised by spectral and temporal variations (Shannon, Zeng, Kamath, Wygonski & Ekelid, 1995). Since speech perception is the basis to develop phonological skills, it is likely that impairments in AM and FM detection affect phonological skill development via speech perception (McBride-Chang, 1996).

However, there are still studies that question the hypothesis of an auditory temporal processing deficit in dyslexia. For example Hill, Bailey, Griffiths and Snowling (1999) and Adlard and Hazan (1998) have not found significant group differences between dyslexics and controls for several tasks of auditory temporal processing. Other investigators, such as Heath, Hogben and Clark (1999) and McArthur and Hogben (2001), have found the deficit only in particular subgroups of dyslexics. Also the evidence for a relationship between auditory temporal processing and phonological skills has not been unequivocal (Marshall, Snowling & Bailey, 2001; Nittrouer, 1999).

To conclude, there are two major lines of studies that have shown an auditory temporal processing deficit in individuals with dyslexia: studies of Tallal and colleagues that

have demonstrated a deficit in processing brief stimuli or stimuli that occur in rapid succession, and studies that have demonstrated a deficit in processing changes in acoustic stimuli such as AM and FM. Most of these studies have been carried out with adults. Nevertheless, there is yet no consensus whether the auditory temporal processing deficit exists in children with dyslexia and how this deficit can be specified. Moreover, it is not clear in what way this deficit can be related to the reading process.

In this study we want to deal with these issues. We tested the hypothesis of an auditory temporal processing deficit in a group of 10- to 12-year old children with dyslexia as compared with a normal reading group of the same age. Auditory temporal processing was assessed by means of two psychophysical threshold tests, one for gap-detection in broadband noise (GAP) and one for 2Hz FM-detection (FM). With the GAP-detection test, Tallal's hypothesis was tested by measuring temporal resolution, i.e. the ability to perceive as separate two events closely occurring in time. With the FM-detection test, we measured the ability to perceive 2 Hz changes in an acoustic stimulus. Assessing both GAP and FM detection ability in the same children with dyslexia and calculating the relations with literacy skills makes it possible to answer three questions. First, whether *children* with dyslexia, in comparison to normal readers, perform significantly worse on psychophysical tasks for auditory temporal processing. Second, whether they perform worse in *both* the GAP and FM detection tasks or just in one of them. Third, whether these temporal processing abilities are *related* to reading and phonological skills. As a consequence, it is possible to determine whether children with dyslexia have an auditory temporal processing deficit and how this deficit can be specified.

Method

Participants

Participants of the experimental group were 6 boys and 4 girls with developmental dyslexia (dyslexic readers; DR). Mean age of the DR-group was 11;4 years (*SD* = 0;9 yr). The participants had been diagnosed as reading disabled by an authorised educational psychology service and were in a special education school for children with specific learning disabilities. Selection criteria were a) native Dutch speaking, b) average or above average intelligence (Wechsler IQ ≥ 85), c) no gross deficiencies in ophthalmology (Snellen acuity > .8) or audiology (audiometric pure-tone thresholds < 20 dB HL at octave frequencies in the range of

250-4000 Hz) and d) scoring below percentile 10 on both of two standardised Dutch word-reading tests: the One-minute Real-Word reading Test (Brus & Voeten, 1973) and the Pseudo-Word reading Test (Van den Bos et al., 1994; see below for a detailed description). Criterion b was used to exclude the so-called "garden variety" poor readers whose literacy is poor because their intelligence quotient is low (see Snowling, 2000, p. 30).

Participants of the control group were 10 normal reading children (normal readers; NR) matched to the experimental group for sex (6 boys) and chronological age (t (18) = -0.35, p = 0.73). Mean age of the NR-group was 11;5 yr (SD = 0;7 yr). Normal readers were selected in the senior classes of a primary school. They met the same criteria as the dyslexic readers for language, intelligence and sensory acuity (see criteria a-c). Since in Flanders children with low IQ are in special education schools instead of regular primary schools, intelligence was not tested, but assumed to be average or above average. NR's performance on both standardised word-reading tests (criterion d) was at least higher than percentile 50.

Informed consent was obtained from all children and from at least one of their parents. During the experiments the children were motivated with small rewards. Detailed characteristics of both participant groups are given in Appendix.

Apparatus

Reading tests

Reading ability was assessed using two standardised Dutch word recognition tests: the One-Minute Real-Word reading Test, RWT (Brus & Voeten, 1973) and the Pseudo-Word reading Test, PWT (Van den Bos et al., 1994). Both tests consist of 116 single words of increasing difficulty. In the PWT, the words (i.e. pseudo-words) have the same syllabic structure than those of the RWT. Participants were instructed to read aloud the words correctly and as quickly as possible. The raw score on the tests is the number of words read correctly in one minute for the RWT, in two minutes for the PWT. Raw scores on RWT and PWT were converted into standard scores with M = 10 and SD = 3 (Van den Bos et al., 1994).

GAP-detection test

In the GAP-detection test, white noise stimuli were used. The target stimulus was a white noise stimulus containing a silent gap. The reference stimulus was an uninterrupted white noise. In the target stimulus, the length of the markers (i.e. the parts of the stimulus

surrounding the gap) varied between 200 and 700 ms. The length of the reference stimulus was 500 or 1000 ms. These different lengths were used to prevent participants from using overall duration as a cue for detection (van Wieringen & Wouters, 1999). Stimuli were cosine gated on and off with 50 ms rise and fall times. Gap rise and fall times were 0.5 ms. Stimuli were generated in MATLAB 5.1 and saved as 16-bit wav-files (sample frequency 44100 Hz) on the hard disc of a Toshiba 486DX4 portable computer. They were presented using a PCMCIA audio PC-card and rooted to an audiometer (Madsen OB622) in order to have control over the level of presentation. The stimuli were presented monaurally (through the right ear) at 65 dB SPL over a calibrated TDH-39 headphone. Testing took place in a quiet room and responses were recorded using a standard computer mouse.

FM-detection test

In the FM-detection test, stimuli can be defined as $A\sin[2\pi f_c t+\beta\sin(2\pi f_m t)]$ in which β is the modulation index ($\beta=\Delta f/f_m$), f_c the carrier frequency, f_m the modulation frequency and Δf the frequency deviation. The target stimulus was a 2 Hz frequency modulation (f_m) of a 1 kHz carrier tone (f_c). The reference stimulus was a pure tone of 1 kHz ($\beta=0$). The length of each stimulus was 1000 ms including 20 ms cosine-gated onsets and offsets. Frequency modulation in the target was sinusoidal and the modulation envelope was always in sine phase. Stimuli were generated and presented in a similar way and with the same equipment and software as in the GAP-detection test (Geurts & Wouters, 2000).

Psychophysical procedure

In both the GAP and FM-test, detection thresholds were estimated using a two interval, two-alternative forced-choice procedure with the target stimulus randomly presented in either the first or the second interval. Intervals were separated by a 500 ms silent inter-stimulus interval. On the computer screen, the intervals were represented by two panels respectively indicated with number 1 and 2. Participants, wearing the headphone, were sitting in front of the computer screen and were required to report verbally which interval, first or second, contained the target. They were given an unlimited time to respond. The experimenter, seated beside the participant, recorded the responses by clicking on the corresponding panel. Immediately after responding, participants were presented with visual feedback on the screen for 2000 ms. After termination of feedback the next trial began.

The length of the gap or the frequency deviation (Δf), according to the test, was adjusted adaptively using a two-down, one-up rule, which targeted the threshold corresponding to 70.7% correct responses (Levitt, 1971). In the GAP-test, each threshold run began with a gap length of 100 ms. The gap length was decreased by a factor of 1.2 from 100 to 10 ms and with a step size of 1 ms between 10 ms and 0 ms. An additional stimulus with a gap length of 0.5 ms was added for those listeners who may even detect a gap smaller than 1 ms. In total 25 different target stimuli were generated. In the FM-test, each run began with a frequency deviation (Δf) set to 2% of the carrier frequency. The frequency deviation (Δf) was decreased by a factor of 1.25. In total 14 different target stimuli were generated. In both tests, a threshold run was terminated after 10 reversals. Thresholds for an individual run were calculated by averaging the values of the last 6 reversals. For each participant, 4 threshold estimates were determined (4 runs on 4 different days for both GAP and FM). These repeated measures were taken to check for potential differences in learning rate. Prior to data collection, participants were given a short period of practice -comprising supra-threshold trials- to familiarise them with the stimuli and the task.

Statistical Analysis

Psychophysical thresholds were analysed using Mixed Model Analysis for repeated measures designs (Littell et al., 1996). Normal quantile plots for thresholds of the different threshold runs did not show extreme skewness or outliers. Mixed Model Analysis was chosen to avoid violating the sphericity assumption of repeated measures designs with three or more treatment levels (Max & Onghena, 1999). In the model the within-subjects factor was threshold run (1 to 4), the between-subjects factor participant group (DR vs NR) and the covariates sex and age. Appropriate covariance structures were modelled as outlined in Littell et al. (1996, p. 101). Relationships between variables were analysed using Spearman correlation coefficients.

Psychophysical control task

To check whether any deficit on the auditory temporal tasks in the DR-group does not result from failing performance on auditory psychophysical tasks in general, the audiometric pure-tone detection task (used in the participant selection procedure) was included in the analysis as a non-temporal control task. In the audiometric detection task, pure-tone thresholds at

octave frequencies in the range of 250–4000 Hz were obtained using the Hughson-Westlake procedure, which is also an adaptive staircase method. Stimuli were presented in a similar way as in the GAP and FM-detection tests and the same equipment was used. Thresholds of the different frequencies were summarised in one index, the so-called Fletcher-index or Pure Tone Average (PTA), which represents the mean hearing loss in dB HL at 500, 1000 and 2000 Hz. The data of the control task were analysed with a t-test for differences in group means.

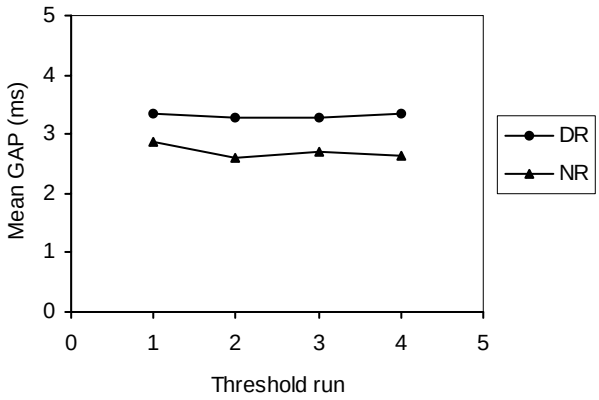
Results

GAP-detection experiment

Participants' individual threshold estimates for GAP-detection are given in Appendix. The mean GAP threshold over all threshold runs was 3.3 ms (*SD* = 0.5 ms) for the DR-group and 2.7 ms (*SD* = 0.3 ms) for the NR-group. For some participants, thresholds of the different runs varied a lot. Mixed Model Analysis showed that there was a significant effect of participant group, $F(1,16) = 12.06$, $p = .003$. There was no significant effect of threshold run, $F(3,16) = 0.39$, $p = .76$ and no significant run by group interaction effect, $F(3,16) = 0.25$, $p = .86$. This means that the thresholds of the dyslexic readers were significantly higher (0.6 ms) than those of the normal readers over the 4 successive threshold runs. Thresholds did not change during the runs, what indicates that there was no training effect, either for dyslexic or for normal readers (Figure 1).

To analyze the relationship between participants' GAP-detection ability and their reading skills, Spearman correlation coefficients were calculated between the participants' average GAP-thresholds of the 4 threshold runs (see AVGAP in Appendix) and their RWT and PWT raw scores. The use of the average threshold was justified, as there was no within-subject effect in the Mixed Model Analysis. Spearman r_s was -0.60 ($p = .005$) for the relationship between AVGAP and RWT and -0.58 ($p = .007$) for the relationship between AVGAP and PWT.

Figure 1 Mean GAP-detection threshold per threshold run for dyslexic (DR) and normal readers (NR).

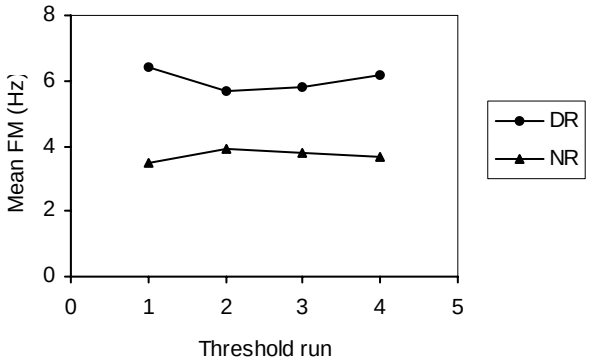


FM-detection experiment

Participants' individual threshold estimates for FM-detection are given in Appendix. The mean FM threshold over all threshold runs was 6.0 Hz (*SD* = 3.3 Hz) for the DR-group and 3.7 Hz (*SD* = 1.2 Hz) for the NR-group. Again, for some participants, thresholds of the different runs varied a lot. Mixed Model Analysis showed that there was a significant effect of participant group, $F(1,16) = 5.06$, $p = .04$, no significant effect of threshold run, $F(3,16) = 0.05$, $p = .98$ and no significant run by group interaction effect, $F(3,16) = 0.41$, $p = .75$. This means that, as for the GAP experiment, the thresholds of the dyslexic readers were significantly higher (2.3 Hz) than those of the normal readers over the 4 successive threshold runs. Thresholds did not change during the runs, indicating that there was no training effect, either for dyslexic or for normal readers (Figure 2).

Spearman r_s was -0.19 ($p = .41$) for the relationship between the participant's average FM-thresholds of the 4 runs (AVFM in Appendix) and RWT, and –0.42 ($p = .07$) for the relationship between AVFM and PWT.

Figure 2 ***Mean FM-detection threshold per threshold run for dyslexic (DR) and normal readers (NR).***

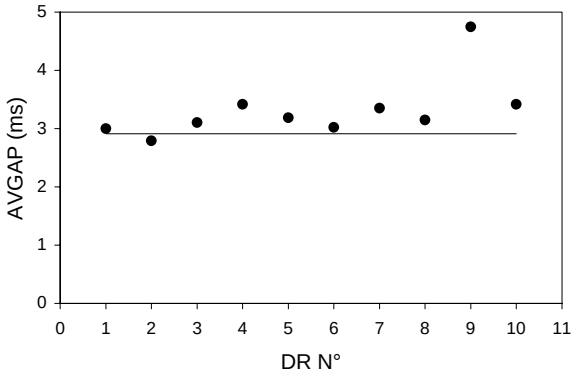


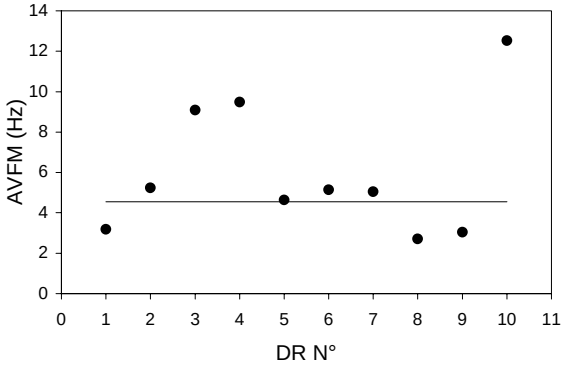
GAP and/or FM-detection deficit?

In Figure 3 (a and b) dyslexic readers' average thresholds of the 4 runs for GAP and FM detection (see AVGAP and AVFM in Appendix) are plotted against the 95% upper confidential level of the respective average thresholds of the normal readers. The figure shows that 6 of 10 dyslexic readers had significantly higher thresholds than the averaged normal readers for both the GAP and FM detection task. For three of the dyslexic readers (n° 1, 8, 9), thresholds were only higher for the GAP, but not for the FM-detection task. For one dyslexic reader (n° 2), the average threshold was higher for the FM, but not for the GAP-detection task. Spearman r_s between AVGAP and AVFM ($r_s = 0.31$, $p = .19$) showed that the relationship between GAP and FM detection ability was not significant.

Figure 3 ***a. Dyslexic readers' average GAP thresholds (AVGAP) in comparison with the GAP 95% upper confidential level for normal readers (horizontal line).***

b. Dyslexic readers' average FM thresholds (AVFM) in comparison with the FM 95% upper confidential level for normal readers (horizontal line).





Control task

The results of the non-temporal control task show that the audiometric pure-tone thresholds are not significantly different for the DR and the NR-group. The mean PTA-threshold was 4.2 dB HL ($SD = 4.9$) for the DR-group and 3.2 dB HL ($SD = 5.1$) for the NR-group ($t\,(18) = 0.45$, $p = .66$).

Discussion

In this study, psychophysical thresholds were estimated for auditory GAP and FM-detection in a group of 10 children with dyslexia (10- to 12-year-old) and 10 age-matched normal reading controls. We tested children because we wanted to determine whether the hypothesis of an auditory temporal processing deficit also applies to children with dyslexia. We administered both GAP and FM-detection ability to determine whether children with dyslexia have problems with both the GAP and FM-detection tasks or just with one of them. Finally, we correlated the temporal detection thresholds with obtained reading and phonological measures to explore the meaning of a possible deficit.

Significant group differences were found for both the GAP and FM-detection test. GAP and FM-detection thresholds of the dyslexic readers were significantly higher than those of the normal readers over the 4 successive threshold runs. Moreover, 6 of 10 dyslexic readers had significantly higher thresholds than the controls for both the GAP and FM-detection test. This means that the dyslexic readers perform worse than the normal readers on both auditory temporal tasks. Thresholds did not change over the successive runs, indicating that there was no training effect, either for dyslexic or for normal readers. This suggests that the dyslexics' temporal deficit not simply results from the fact that they need more time to learn a difficult psychophysical task. Equal performance on the non-temporal control task also confirms that the significant higher thresholds of the dyslexic readers on both the GAP and FM-detection task is likely to result from a specific temporal processing deficit, rather than a failing performance on auditory psychophysical tasks in general.

Concerning the relationship between auditory temporal psychophysical thresholds and literacy skills, we found significant negative correlations between GAP-detection thresholds and reading and phonological scores. This confirms that the observed group difference for

GAP-detection between the DR and NR-group can be related to a difference in literacy. On the contrary, the FM-detection thresholds are not correlated with reading or phonological measures. This indicates that the observed group difference for FM-detection is not related to the specific difference in literacy between the DR and NR-group. Instead, it suggests that the observed FM group difference results from another underlying third factor that is not specific to dyslexia but unequally represented in both groups (for example intelligence). Moreover, the finding that GAP and FM-detection thresholds are not mutually related also indicates that both auditory tasks measure different processing skills that might rely on a different underlying processing mechanism.

The group differences on the GAP-detection experiment are not consistent with findings of other studies that used a gap detection paradigm (Adlard & Hazan, 1998; McAnally & Stein; 1996, Schülte-Korne et al., 1998). However, it is difficult to compare our study with these studies. McAnally and Stein tested adult subjects and Schülte-Korne et al. and Adlard and Hazan reported mean gap thresholds that were significantly higher than our average thresholds. In the latter study, this can easily be understood because the smallest gap that could be technically administered in the test was 4 ms, which is larger than the thresholds that we found. Moreover, different psychophysical procedures were used. Nevertheless, our GAP-detection results do confirm those of McCroskey and Kidder (1980). They are thus in line with Tallal's original findings (1980) and Nagarajan et al.'s replication of these findings (1999) that children with dyslexia require a longer inter-stimulus interval to perceive brief acoustic stimuli that occur in rapid succession. Our observed correlations between GAP-detection thresholds and phonological measures are also in line with Tallal's original data. However, they are conflicting with the findings of Marshall, Snowling and Bailey (2001) who could not find any evidence for a relationship between phonological skills and rapid auditory processing.

A possible neurophysiological explanation for this observed deficit in auditory temporal resolution is that dyslexic readers have a prolonged refractive period in their neurological firing pattern. This may be the result of a slower transmission time of neural information (Stein & Walsh, 1997). A similar temporal resolution deficit has been found in the visual modality where it has been related to a subtle impairment in a specific visual subsystem, namely the magnocellular system (Lovegrove, 1996; Van Ingelghem et al, 2001). This system, characterised by large and heavily myelinated axons, is particularly responsible for processing fast and transient information. Although the auditory system does not have an anatomically distinct magnocellular pathway, there is supposed to be an auditory subsystem

that is responsible for analysing acoustic transients (see Stein & Talcott, 1999). This auditory subsystem should be similarly characterised by large neurones and located in the medial geniculate nucleus (MGN). Galaburda and colleagues have demonstrated that, like visual magnocells, auditory 'magnocells' in the MGN show abnormalities in the brains of dyslexic readers (Galaburda, Menard & Rosen, 1994; Livingstone, Rosen, Drislane & Galaburda, 1991). Even though the existence of a similar magnocellular fast-transmitting auditory subsystem is still controversial, the results on the GAP-detection experiment do at least suggest impairment in this system for dyslexics.

The group differences on the FM-detection experiment are conflicting with the findings of Adlard and Hazan (1998) and Hill et al., (1999). However, it is again difficult to compare with these studies. In the first study, FM rates were higher (between 60 and 300 Hz) than in our study. Similarly, Witton et al., (1998) failed to find impaired FM sensitivity in dyslexic readers with 240 Hz FM (probably because at higher modulation rates FM detection depends mainly on spectral instead of temporal cues). The lack of significant differences in the study of Hill et al. (1999) might be attributed to the small difference between the dyslexic and control group's phonological skills (see Talcott & Witton, 2002). It is also difficult to compare with Hill's study because adult samples were used. Converging evidence for the observed group differences on the FM detection task is found in both Witton's studies on adult samples (Witton et al., 1998, 2002).

In the present study we didn't find any significant correlation between FM-detection thresholds and scores on a real word reading and pseudoword reading task. However, Talcott, Witton and colleagues consistently found significant correlations between reading and phonological measures and FM-detection skills with a slow modulation rate as the 2 Hz FM. These correlations were found in studies with dyslexic and normal reading adults (Witton et al., 1998, 2002), as well as in studies with unselected children covering the normal range of reading abilities (Talcott et al., 1999, 2000, 2002). However, they never conducted a comparable child study with contrasting DR and NR-groups. Moreover, their use of a psychophysical paradigm with constant stimuli differs from our adaptive staircase procedure, which offers a more optimal learning situation due to a gradual increase in stimulus difficulty. On the other hand, our observed correlation with phonology is not negligible (r_s = -0.42, p = .07) and almost reaches significance. It is very probable that significance would have been reached when more subjects were included in the study.

An alternative explanation for the conflicting FM results can be found in the impact of intelligence on any measured variable. As Hirsh and Watson (1996) have shown, the variance

in psychophysical task performance is associated with individual differences in cognitive skills. This means that our correlations can be blurred by a non-perfect matching of intelligence. From the three psychophysical tasks we administered, the FM-detection task is conceptually the most difficult one and, consequently, the most sensitive to differences in general intelligence. Future studies will include a larger sample of IQ-matched subjects to avoid this possible interference.

To conclude, we found evidence that dyslexic reading children perform worse than normal reading controls on both auditory temporal processing tasks. However, both temporal impairments are unrelated to each other, suggesting that they might depend on different underlying mechanisms. Moreover, GAP-detection seems to be a reading and phonology related (and as such a dyslexic-specific) deficit. On the contrary, FM-detection seems to be unrelated to reading and phonological skills.

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Appendix: Participants' Characteristics, Reading Scores and Psychophysical Threshold Estimates

Group	N°	Sex	Age	RWT	PWT	GAP1	GAP2	GAP3	GAP4	AV GAP	(*SD*)	FM1	FM2	FM3	FM4	AV FM	(*SD*)
DR	1	f	148	1	1	2,3	3,4	3,3	2,9	3,0	(0,5)	5,9	1,8	2,7	2,3	3,2	(1,8)
DR	2	m	141	1	1	2,3	3,2	2,4	3,3	2,8	(0,5)	6,4	2,9	6,7	5,0	5,2	(1,7)
DR	3	f	126	1	1	3,8	3,6	2,0	3,1	3,1	(0,8)	14,9	8,2	3,1	10,2	9,1	(4,9)
DR	4	m	125	1	1	3,4	3,5	3,3	3,4	3,4	(0,1)	9,3	12,2	6,9	9,6	9,5	(2,2)
DR	5	m	147	1	2	3,4	3,3	2,5	3,5	3,2	(0,5)	5,6	4,2	4,8	3,9	4,6	(0,8)
DR	6	F	142	1	2	3,9	1,8	2,7	3,7	3,0	(1,0)	2,8	4,4	8,5	4,9	5,1	(2,4)
DR	7	m	140	1	3	3,3	3,3	3,3	3,6	3,4	(0,2)	4,1	6,3	6,5	3,3	5,1	(1,6)
DR	8	m	135	1	3	3,3	3,7	2,7	3,0	3,1	(0,4)	3,5	1,4	2,2	3,8	2,7	(1,1)
DR	9	m	125	1	5	4,3	3,7	7,5	3,5	4,8	(1,9)	4,4	1,9	3,0	2,9	3,0	(1,0)
DR	10	f	130	3	5	3,6	3,5	3,1	3,5	3,4	(0,2)	7,3	13,4	13,6	15,9	12,5	(3,7)
M			136	1,2	2,4	3,4	3,3	3,3	3,4	3,3		6,4	5,7	5,8	6,2	6,0	
SD			9,1	0,6	1,6	0,6	0,5	1,5	0,3	0,5		3,5	4,3	3,5	4,3	3,3	
NR	1	m	132	10	10	3,3	3,4	3,0	2,8	3,1	(0,3)	4,4	4,4	2,8	4,8	4,1	(0,9)
NR	2	m	147	11	11	2,3	2,4	2,0	2,1	2,2	(0,2)	1,7	1,8	1,6	1,8	1,7	(0,1)
NR	3	m	146	12	16	3,3	2,8	2,5	1,8	2,6	(0,7)	3,9	4,7	2,1	2,4	3,3	(1,2)
NR	4	m	128	12	16	2,5	1,9	3,3	2,8	2,6	(0,6)	3,5	2,6	4,6	4,8	3,9	(1,0)
NR	5	f	127	12	19	2,6	2,8	2,6	2,8	2,7	(0,1)	3,6	2,0	4,8	2,8	3,3	(1,2)
NR	6	m	137	13	12	3,3	2,6	1,9	3,3	2,8	(0,7)	4,1	4,0	4,3	4,7	4,3	(0,3)
NR	7	m	134	13	15	2,7	2,9	3,0	2,7	2,8	(0,2)	3,0	3,3	2,7	2,8	2,9	(0,3)
NR	8	f	135	14	15	3,0	2,6	3,5	3,5	3,1	(0,4)	3,1	5,5	2,3	3,2	3,5	(1,3)
NR	9	f	144	16	12	3,0	2,2	2,2	2,3	2,4	(0,4)	4,2	6,9	8,8	5,6	6,4	(2,0)
NR	10	f	145	19	16	2,7	2,6	3,1	2,6	2,7	(0,2)	3,6	3,8	3,6	3,6	3,6	(0,1)
M			137	13,2	14,2	2,9	2,6	2,7	2,6	2,7		3,5	3,9	3,8	3,7	3,7	
SD			7,4	2,6	2,8	0,4	0,4	0,6	0,5	0,3		0,8	1,6	2,1	1,3	1,2	

Note: Group: DR: dyslexic readers, NR: normal readers / N°: participant number / Sex: f: female, m: male / Age: age given in months / RWT: standard scores on Real Word reading Test (M = 10, SD = 3) / PWT: standard scores on Pseudo-Word reading Test (M = 10, SD = 3) / GAP1-4: GAP thresholds in ms from run 1-4 / AVGAP (*SD*): average GAP thresholds in ms from the 4 runs (standard deviation) / FM1-4: FM thresholds Δf in Hz from run 1-4 / AVFM (*SD*): average FM thresholds Δf in Hz from the 4 runs (standard deviation).