Temporal Processing Performance, Reading Performance, and Auditory Processing Disorder in Learning-Impaired Children and Controls

Traitement temporel, performance en lecture et troubles de traitement auditif chez des enfants souffrant de déficits d'apprentissage et des enfants témoins

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Abstract

This paper examines the relations between temporal processing and reading performance by comparing the performance of 38 children with learning impairments (LI) to 32 age-matched, typically developing subjects (controls) on these tasks. Subjects were tested on four auditory and four visual temporal processing tasks, and four language/reading tasks. Subjects in the LI group were also tested for auditory processing disorder (APD). Kruskal-Wallis tests and Spearman correlation coefficients were used to evaluate the differences and relations between group test scores (alpha = 0.05, Bonferroni corrected). LI subjects performed more poorly than controls on reading and phonological awareness tasks, as well as on the subset of temporal processing tasks that required the relative timing of two stimulus events. There was a trend for performance on language/reading and several auditory temporal processing tasks to drop from control subjects, to those with LI alone, to those with both APD and LI. Scores on a subset of relative timing tasks were positively correlated with reading scores for controls, but not LI subjects. The results suggest that relative timing judgements of auditory and visual stimuli, rather than the identification of a single, brief stimulus event, may play a key role in reading development.

Abrégé

Cet article examine les liens entre le traitement temporel et la performance en lecture. L'étude compare les résultats de 38 enfants ayant des déficits d'apprentissage (DA) à ceux de 32 enfants du même âge (témoins) démontrant un développement normal de ces fonctions et compétences. Les sujets ont exécuté quatre exercices portant sur le traitement temporel visuel et quatre exercices portant sur le langage et la lecture. Les sujets du groupe DA ont aussi été testés pour des troubles de traitement auditif (TTA). Les tests Kruskal-Wallis et les coefficients de corrélation de Spearman ont été utilisés pour évaluer les différences et les relations entre les résultats des tests du groupe (alpha = 0,05, correction de Bonferroni). Les sujets du groupe DA ont eu des résultats inférieurs à ceux des sujets témoins dans les exercices de lecture et de conscience phonologique, ainsi que dans les exercices de traitement temporel qui nécessitaient la synchronisation de deux stimuli. On a observé une tendance en langage/lecture et dans plusieurs exercices de traitement temporel auditif où les résultats baissaient des sujets témoins, aux sujets avec DA à ceux souffrant de TTA et DA. Les résultats d'une série d'exercices de synchronisation relative étaient positivement en corrélation avec les résultats en lecture chez les sujets témoins, ce qui n'était pas le cas chez les sujets avec DA. Les résultats ont démontré que les analyses de synchronisation relative de stimuli auditifs et visuels pourraient jouer un rôle essentiel dans le développement de la lecture plutôt que l'identification d'un seul stimulus précis.

Key words: auditory processing disorder, temporal processing, audition, vision, reading, and language

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Abbreviations:

Auditory Processing Disorder (APD), degrees of freedom (df), Inter-Stimulus Interval (ISI), Learning-Impaired (LI), Comprehensive Test of Phonological Processing (CTOPP), Stimulus Onset Asynchrony (SOA), Temporal Order Judgment (TOJ), Wide Range Achievement Test 3 (WRAT-3).

A significant task for hearing science is the characterization of auditory processing deficits and their relation to higher cognitive function. One growing body of research has suggested that sensory temporal processing plays a key role in language and reading proficiency. Individuals with dyslexia are impaired on many tasks that require the perceptual elaboration of temporally proximate and brief stimuli (Tallal, 1980a) or the efficient processing of stimulus cues over short time frames (Hartley, Hill, & Moore, 2003; Hill & Raymond, 2002). Furthermore, performance on temporal processing and language tasks has been shown to be correlated in unimpaired readers (Au & Lovegrove, 2001a, 2001b; Talcott et al., 2002; Witton et al., 1998). We have previously shown that performance in temporal processing tasks relevant to or independently associated with language function develops before or in parallel with language function in children who are unselected for reading level (Walker, Hall, Klein, & Phillips, 2006). This developmental trajectory is consistent with the proposed causal role of temporal processing in language and reading development (Tallal, 1980b).

Several studies have suggested that the relationship between temporal processing and reading performance may be subdivided according to sensory modality, such that auditory temporal processes predict variation in phonological aspects of reading, and visual temporal processes explain orthographic performance (Au & Lovegrove, 2001a; Farmer & Klein, 1995; Witton et al., 1998). However, we have reported data which suggest that it is the type of temporal demand of a perceptual task, rather than the sensory modality in which it is presented, that determines its relation to phonological aspects of reading performance (Walker et al., 2006). In particular, we found that relative timing processes, as opposed to temporal-event detection tasks, contributed unique variance to phonological processes in reading. This effect was especially robust in, but not restricted to, the auditory modality (Walker et al., 2006). In this regard, one recent study of auditory temporal gap detection in children with and without auditory processing disorder (APD) showed explicitly that those with APD were impaired on relative timing judgements but not on temporal event detection ones - a point which derived special significance from the fact that the particular relative timing processes studied were independently implicated in speech perception (Phillips, Comeau, & Andrus, 2010).

On the other hand, some authors fail to find correlations between these factors within dyslexic populations (Heiervang, Stevenson, & Hugdahl, 2002; Rosen, 2003). Other authors point out that the relationship between any kind of specifically auditory temporal processing disorder and higher cognitive function may be more complicated than previously suspected (Rosen and Manganari, 2001; Ramus et al., 2003; Bishop et al., 1999). Part of the difficulty here may lie in the heterogeneity of APD and in any imprecision with which its behavioural expression is sought (Cacace & McFarland, 1998; Musiek, Bellis, & Chermak, 2005; Jutras et al., 2007). This difficulty is not surprising from the neurological standpoint because there has yet to be presented any evidence of a consistent focal neurological defect in APD. It is quite possible that an APD, like reading disorders, could reflect any number of diffusely patterned afflictions of neural networks which happen to include auditory ones, but which because of their heterogeneity have diverse behavioural expressions. In this regard, efforts to develop diagnostic criteria for APD, and especially ones that isolate specifically auditory processing deficits from other more general perceptual and cognitive ones, may be both laudable but fraught with the difficulty that derives from the awkwardness of separating perceptual and cognitive processes.

The present study expands on earlier work by examining the same temporal processing and reading measures that we have examined previously in normally-developing children in learning-impaired (LI) children, all of whom had undergone a full audiological examination, and some of whom tested positive for APD. We investigated whether learning-impaired subjects and age-matched controls differed on phonological and orthographic aspects of reading performance, and on a battery of eight visual and auditory temporal processing tasks. If a basic temporal processing impairment is correlated with reading proficiency, one might expect individuals with a positive APD diagnosis to be particularly impaired in both reading tasks and those temporal processing tasks that have previously been shown to relate to reading performance. In the relatively few previous studies that have investigated the performance of impaired readers on standard APD test batteries, an increased incidence of APD has been found within impaired readers (Cacace & McFarland, 1998; Demanez, Boniver, Dony-Closon, Lhonneux-Ledoux, & Demanez, 2003; Sharma et al., 2006; Welsh, Welsh, & Healy, 1980). It was found that learning-impaired individuals perform more poorly than age-matched controls on phonological awareness and reading tasks, and additionally on temporal processing tasks that require the relative timing of two stimulus events. This deficit was most robust in the auditory modality, although impairments were also found on tasks that required the relative timing of rapid visual cues. Furthermore, there was a trend for the subgroup of individuals with a learning impairment and APD to consistently perform more poorly on reading, phonological awareness and auditory temporal order judgment tasks than LI subjects without APD. However, the presence of an APD alone was unable to account for the impairment in temporal processing and reading performance observed in LI subjects.

Methods

Subjects

Subjects were 11 to 14 years old on the date of testing. Control subjects (n = 32; mean age = 12.6 years, standard deviation = 1.1 years) were recruited by word-of-mouth from Nova Scotia, Newfoundland and Alberta. Data from these subjects have been presented in a previous publication (Walker et al., 2006). LI subjects were recruited from a school for students with various kinds of learning impairments in Calgary, Alberta (n = 38; mean age = 12.2 years, standard deviation = 1.1 years). Here, we did not select subjects within the LI group based any particular type of learning impairments as long as they could complete the tasks of the study. This group is likely to include subjects who have attention deficit disorders, language and reading impairments, and more general developmental learning impairments. Detailed information on the incidence of diagnosed attention or reading disorders within this participant group is unavailable to report here, but all children in this school were diagnosed with a learning impairment by an educational psychologist. The diagnosis was based on their relatively poor school performance in the face of normal overall cognitive function (full-scale IQ scores of 85 or greater, as measured on the Wechsler Intelligence Scale for Children III and/or the Peabody Individual Achievement Test).

The heterogenity of this participant pool might nevertheless be regarded as a problem for this study. We note, however, that all children in this study were able to complete the clinical and experimental tasks, and that attentional and other cognitive factors appear to play only minor roles in performance of the tasks required for diagnosis of APD or dyslexia (Illadou et al., 2009; Sharma et al., 2009; Cohen-Mimran & Sapier, 2009; Dawes et al., 2009).

Ethical approval for this research was granted by the Research Ethics Board of Dalhousie University and the Conjoint Health Research Ethics Board of the University of Calgary. A standard audiogram was obtained on a GSI 16 (Grason-Stadler) or a Madsen audiometer (Otometrics).

All subjects in the present dataset were found to have normal tone thresholds from 0.25 to 8.0 kHz. Subjects were reported by their caregiver to have normal or corrected-to-normal vision (e.g. prescription eyeglasses).

Auditory Processing Disorder Diagnostic Testing

A battery of diagnostic tests of APD was carried out with each subject in the LI group by a registered audiologist. The test battery included the Dichotic Digits, Random Gap Detection, Competing Sentences, Pitch Pattern Sequence, Staggered Spondaic Word and Filtered Words tests. APD was diagnosed when a subject's scores on two or more tests in the battery were at least two standard deviations below published norms, in the absence of confounding variables such as cognitive factors, motivation and inconsistent performance. This type of diagnostic procedure has been described in detail in previous sources (Bellis, 2003; Chermak & Musiek, 1997; Willeford & Burleigh, 1985). Using this approach, ten of the LI subjects were found to meet the criteria for an APD diagnosis (APD+), while the remaining 28 did not (APD-). At the time of APD assessment, the audiologist had access to educational psychological test results and school history data. Children with the poorest cognitive assessments were scored against cognitive-age matched norms, rather than chronological-age matched norms (approximate n = 5).

Temporal Processing Tasks

Full descriptions of the eight temporal processing and five language tasks are provided in Walker et al. (2006), and so they are described only summarily here.

The temporal processing tasks were originally chosen on the basis of either an empirically demonstrated link to language and reading disorders, or because of a theoretical link to language function. The tasks and stimuli were programmed using MATLAB 5 (The MathWorks Inc.) and were presented to subjects on laptop computers (Apple iBook and PowerBook; Apple Canada). Sounds were presented binaurally at a comfortable listening level over headphones (HD 25-1; Sennheiser Canada). Visual stimuli were presented on the laptop computer screen approximately 60 cm in front of the subject, and answers were given by the subject as key presses (iKP-18 USB keypad; Adesso).

Testing on each task was preceded by at least two perceptually "easy" practice trials, which the subject repeated until the experimenter was confident that he or she understood the task. Test trials were then presented at three levels of difficulty using the method of constant stimuli, with the easiest level presented first and the most difficult last. Visual feedback was given after every trial, and subjects paced the trial presentations with a "go" key. The order in which the eight temporal processing and five language tasks were carried out was varied across subjects.

Four auditory temporal processing tasks were carried out: within-channel gap detection, between-channel gap detection, sequential auditory temporal order judgment (TOJ) and overlapping auditory TOJ. In each trial of the within-channel gap detection task, the subject was asked to indicate which of two successive 400-ms bursts of white noise contained a brief silent period ("gap") at its temporal midpoint. The duration of the gap was 24, 8, and 3 ms in the easiest, moderate, and most difficult testing condition, respectively. The between-channel gap detection task was similar to the within-channel version, but here the noises bounding the silent period had different spectral compositions. The first 200 ms of the noise was bandpass filtered from 1800 to 3000 Hz, and the final 200 ms was bandpassed from 800 to 2000 Hz. Gaps of 200, 80, and 30 ms duration were tested. What distinguishes the two gap detection tasks is that the former reduces to a simple discontinuity ("temporal event") detection task in the perceptual channel activated by the stimulus. In contrast, the between-channel task requires a relative timing of the offset of the leading noise and the onset of the trailing one (Phillips et al., 1997, 2010). The acuity of the between-channel mechanism, but not that of the within-channel one, has been implicated in the formation of phonetic boundaries for the voice onset time (Phillips & Smith, 2004; Elangovan & Stuart, 2008). In the temporal order judgment tasks, two 75-ms tones were presented on each trial, and each tone was either "low" (260 Hz) or "high" (690 Hz) in frequency. On the sequential TOJ task, the tones were presented sequentially, with an inter-stimulus interval (ISI) of 400, 84, or 0 ms. The subject was asked to repeat the order of the tones by key press (labelled "high" and "low"). On the overlapping TOJ task, the two tones were presented together, but with a temporal asynchrony in their onsets, and the subject was asked to indicate whether the high or low tone began first. The stimulus onset asynchrony (SOA) was set to 614, 200, and 50 ms in the easy, moderate and difficult condition, respectively.

We also carried out four temporal processing tasks in the visual modality. These included two visual TOJ tasks that were similar to their auditory versions. The stimuli used were images of equally spaced, black, parallel lines on a white background. The lines on each image were either vertically or horizontally oriented. On the sequential TOJ task, two of these images were sequentially presented for 250.5 ms each, with an ISI of 24, 5, or 0 ms between them. The subject was asked to report the order of the images using labelled keys. On the overlapping TOJ task, the two images were presented superimposed on each other (appearing as a grid), but with a variable SOA in their onset. Subjects were asked to indicate which image appeared first, and the task was carried out at SOAs of 38, 12, and 3 ms. The stimuli for the final two temporal processing tasks were random dot kinematograms. In the coherent motion detection task, 35%, 25%, or 15% of the dots in each frame moved coherently in one direction to the following frame, while the remaining dots moved independently in a random direction (up, down, left, or right). The subject was asked to report the direction of motion observed in a 200-ms long random dot kinematogram of this type. In the transparent motion version of this task, half of the dots moved together in a given vertical direction and other half moved coherently in a given horizontal direction. The subjects were asked to indicate both directions of motion observed after viewing this type of kinematogram for 40, 20, or 10 frames (i.e., 1332, 666, or 333 ms). All visual stimuli were designed to subtend about 2.35 degrees of visual angle. Performance on this task has specifically been linked to dyslexia in a previous study (Hill & Raymond, 2002). All clinical (APD) and experimental (temporal processing) testing was paced according to the attentional or other needs of the participants, and all participants were tested individually.

Language and Reading Tasks

Four tests of language and reading performance were carried out: the Phonological Awareness Quotient Subtest of the Comprehensive Test of Phonological Processing (CTOPP; Wagner, Torgesen, & Rashotte, 1999), the reading subtest of the Wide-Ranging Achievement Test-3 (WRAT-3; Wilkinson, 1993), and short versions of the Olson Phonological (Olson PHONO) and Olson Orthographic (Olson ORTHO) subtests (Olson, 1985). The Token Test, a standard test of language reception used to diagnose aphasia (Boller & Vignolo, 1966; Orgass & Poeck, 1966), was also carried out for each subject. In this task, the subject is asked to perform manual manipulations of coloured plastic shapes, according to spoken instructions. This test was included as a control for aphasia, rather than to provide a precise measure of language function. Only one subject was found to perform below the normal range on this task (a subject in the LI, APD- subgroup). Removing this subject from our analysis did not change the statistical significance of any of our results.

Methodological details of the other four language tests are available in Walker et al. (2006), and in their original sources (Olson, 1985; Wagner et al., 1999; Wilkinson, 1993). Briefly, the CTOPP comprised two sections: the Elision and Blending Words tests. In the Elision test, subjects were asked to remove phonological segments from spoken words, and in the Blending Words test, they combined speech sounds to form words. In the reading subtest of the WRAT-3, subjects were asked to read a list of words aloud, in order to assess their ability to read words in the absence of semantic cues. The Olson reading tests contains two parts, which serve to distinguish between subjects' ability to use phonological (i.e. matching sounds to letter sequences) and orthographic (i.e. memorizing the whole word associated with a letter string) strategies. Letter strings are presented in pairs on a sheet of paper, and the subject is asked to pick one string in each pair. In the orthographic subtest, both strings sound like real words when read aloud, but the subject must choose which of the pair is a legally spelled word. In the phonological subtest, neither of the strings spells a real word, but the subject must indicate which one sounds like a real word when read aloud. For the WRAT-3 and CTOPP, it is possible to age-normalize scores, based on a wealth of normative data. However, the data are not available to age-normalize scores on our short form of the Olson reading tests or many of the temporal processing tasks. Therefore, subjects' performance on all our tasks is reported as the percent of trials performed correctly. If trials were skipped, according to floor or ceiling effect rules, these were included in the percent correct calculation as incorrect or correct, respectively.

Results

Descriptive statistics

The distributions of overall percent-correct scores on each task were plotted as histograms. A visual inspection of these plots identified ceiling effects in the within-channel gap detection and Token test scores of LI subjects, and the within-channel gap detection, Token test, and Olson orthographic scores of control subjects. Otherwise, the results of each task were more normally distributed, but often with a negative skew. For these reasons, non-

Table 1
Kruskal-Wallis tests of performance differences between control and LI subjects on temporal processing tasks.

	Within-channel gap detection	Between-channel gap detection	Sequential auditory TOJ	Overlapping auditory TOJ	Sequential visual TOJ	Overlapping visual TOJ	Coherent motion detection	Transparent motion detection
Difficult	χ^2 = 9.81 p = 0.002	χ^2 = 13.84 p < 0.001	χ^2 = 10.51 p = 0.001	χ^2 = 2.98 p = 0.084	χ^2 = 9.09 p = 0.003	χ^2 = 8.11 p = 0.004	χ^2 = 2.82 p = 0.093	χ^2 = 0.12 p = 0.726
Moderate	χ^2 = 0.67 p = 0.415	χ^2 = 17.26 p < 0.001	χ^2 = 12.83 p < 0.001	χ^2 = 18.58 p < 0.001	χ^2 = 3.74 p = 0.053	χ^2 = 3.10 p = 0.079	χ^2 = 0.14 p = 0.705	χ^2 = 0.57 p = 0.451
Easy	χ^2 = 1.60 p = 0.205	χ^2 = 10.19 p = 0.001	χ^2 = 14.37 p < 0.001	χ^2 = 12.13 p < 0.001	χ^2 = 4.81 p = 0.028	χ^2 = 0.17 p = 0.684	χ^2 = 0.01 p = 0.944	χ^2 = 0.23 p = 0.128

Chi squared values (χ^2) and significance levels (p) are shown for Kruskal-Wallis tests comparing control and LI subjects' performance on 3 levels ("difficult", "moderate" and "easy") of each of 8 temporal processing tasks. The Bonferroni-corrected alpha was 0.0063, with 1 degree of freedom.

parametric Kruskal-Wallis tests were used to test for overall differences among subject groups, and Tukey's Honestly Significant Difference (Tukey's HSD) test was used to subsequently make *post hoc*, pair-wise comparisons of subject groups. Jonckheere-Terpstra tests were used to test for one-tailed trends in the data (Jonckheere, 1954), and non-parametric Spearman correlations were used to examine the correlations between test scores. We used an alpha of 0.05, with Bonferroni corrections for statistical comparisons carried out across multiple language/reading or perceptual tasks.

Language and Reading tasks

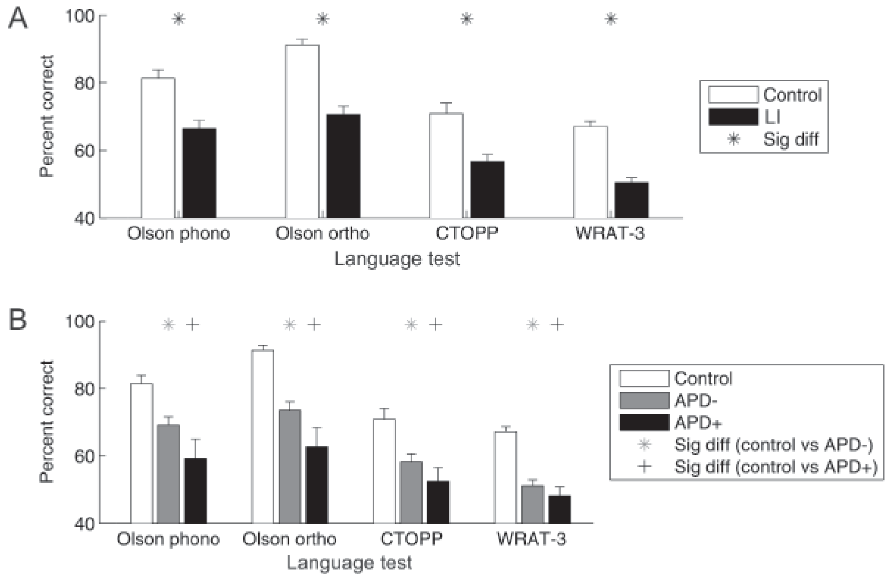
Group mean data from the language tasks are shown in Figure 1. In the upper panels, data are shown for control and LI subjects. In the lower panels, the LI group is broken down into those diagnostically negative and positive for auditory processing disorder. Learning-impaired subjects performed more poorly than controls on the Olson Phonological, Olson Orthographic, CTOPP, and WRAT-3 tests (Kruskal-Wallis test; χ^2 = 31.44, 15.17, 13.22, and 35.87, respectively; degrees of freedom = 1; $p <$ 0.05/5). No significant group differences were found on the Token Test scores (χ^2 = 1.92; df = 1; p = 0.17). When the LI group was broken down into subjects with and without an APD diagnosis, the effect of subject group persisted in all 4 language/reading tasks (Kruskal-Wallis test; χ^2 = 32.72, 16.30, 14.04 and 36.67, for the Olson Phonological, Olson Orthographic, CTOPP and WRAT-3, respectively; df = 2; p < 0.05/5). Again, scores on the Token Test did not differ across subject groups (χ^2 = 2.55; df = 1; p = 0.28). *Post hoc*, pair-wise comparisons showed that the scores of controls differed from those of both LI subgroups on all four language/reading tasks (Figure 1B; Tukey's HSD tests). Although there were no statistically significant differences between the LI subjects who tested positive for auditory processing disorder (APD+) and those who tested negative (APD-), inspection of the data revealed that the rank ordering of subject group performance on every other language-related task was the same: controls, APD- and APD+ (Fig. 1, lower). Therefore, we tested whether there was a statistically significant trend for scores on each of these reading and language tests to decrease across subject groups, from controls, to APD- and APD+. This trend was statistically significant on all four tasks (Jonckheere-Terpstra Test; JT = 4.04, 5.78, 3.80 and 6.08 for the Olson Phonological, Olson Orthographic, CTOPP and WRAT-3, respectively; p < 0.05/5). This trend in the data suggests that the presence of APD may be associated with further impairment of reading performance within individuals already having general learning impairments. If the reading (WRAT-3, Olson tests) and phonological awareness (CTOPP) impairments observed here are at least partially due to, or associated with, a general temporal processing impairment in the LI subjects, we might expect to see associated deficits in performance for this group on relevant temporal processing tasks.

Temporal Processing Tasks

Group mean data from the temporal processing tasks are shown in Figures 2 and 3. Kruskal-Wallis tests were carried out to examine whether the performance of LI and control subjects differed for each level of the eight temporal processing tasks (Table 1; alpha = 0.05/8; df = 1). These analyses showed that the LI group performed more poorly than the control group on some, but not all, of the temporal processing tasks in our test battery (summarized in Fig. 2). In general, we found that group mean performance on relative timing tasks, especially in the auditory modality, was systematically poorer in LI subjects. LI subjects performed more poorly than controls on all levels of the between-channel gap detection and sequential auditory temporal order judgment (TOJ) tasks. LI subjects also showed impairments on the overlapping auditory temporal order judgment task, but not when the task was presented at the most challenging difficulty level. For the within-channel gap detection task, LI subjects performed more poorly than control subjects, but only when the gap was at the minimum duration of 3 msec.

There was modest evidence that a sensory processing

Figure 1: Reading and receptive language performance of all subject groups. Upper panel depicts group mean percent-correct scores on the four language/reading tasks, plotted separately for control and learning-impaired subjects. Error bars are standard errors of the mean, and asterisks indicate group mean differences that are significant at p < 0.05/5. Lower panel shows the same data, but with the learning-impaired group divided into those diagnostically negative (grey bars) or positive (black bars) for APD. Significant group mean differences (p < 0.05/5) between control and APD- (asterisks) subjects and control and APD+ (crosses) subjects are shown.



deficit extended to visual TOJ tasks, but as in the case of within-channel gap detection, LI subjects were only impaired on the most difficult visual ordering conditions. Performance was not at ceiling on the motion detection tasks, and no significant group differences were found on these tasks.

When the analysis of temporal processing performance was repeated with the LI group divided into two groups according to the presence (APD+) or absence (APD-) of an auditory processing disorder, there was a significant effect of subject group on performance within four of the eight temporal processing tasks: the difficult condition of the within-channel gap detection task, all three levels of the between-channel gap detection and sequential auditory TOJ tasks, and the easy and moderate levels of the overlapping auditory TOJ (see Table 2 for test results). The results of Tukey's HSD pairwise comparisons are summarized in Figure 3. This analysis showed that only the group of LI subjects without APD (asterisks in Fig. 3) performed more poorly than controls on the between-channel gap detection task. On the two auditory TOJ tasks, LI subjects who were APD+ (crosses in Fig. 3) performed more poorly overall than control subjects, except for the most difficult condition of the overlapping auditory TOJ. The APD- subjects also performed more poorly than age-matched controls on the intermediate level of the overlapping auditory TOJ task.

Although the mean score of APD+ subjects was consistently lower than the APD- subjects on the auditory TOJ tasks, Tukey's HSD tests did not reveal any statistically significant differences between these two groups on any of the temporal processing tasks. However, as in the case of the language and reading tasks, the results of some of the temporal processing tasks showed a trend in increasing scores across the APD+, APD- and control groups, as would be predicted if the presence of APD and learning deficits had cumulative, negative effects on temporal processing performance. Therefore, we tested for the significance of this trend in our data on each task, at each difficulty condition (Jonckheere-Terpstra Test; alpha = 0.05/8). We found this trend to be significant for the most difficult condition of the within-channel gap detection task (JT = 3.23), all conditions of the between-channel gap detection task (JT = 2.98, 3.81 and 3.23 for the easy, moderate and difficult conditions, respectively) and auditory sequential TOJ tasks (JT = 4.04, 3.69 and 3.67 for the easy, moderate and difficult conditions, respectively), and the two easiest conditions of the auditory overlapping TOJ task (JT = 4.10 and 4.59 for the easy and moderate conditions, respectively). This trend was also present for the most difficult conditions of the sequential (JT = 2.60) and overlapping (JT = 2.64) visual TOJ tasks.

Correlations between Temporal Processing and Language Scores

Spearman correlation coefficients were calculated to test for relations between individual subjects' scores on the temporal processing and language/reading tasks. Scores on the three levels of each temporal processing task were pooled into an overall percent correct score. When the data for all 70 subjects were pooled, significant (if moderate) positive correlations were found between scores on the Olson phonological test and the between-channel gap detection task, the auditory overlapping TOJ task, and the

Table 2
Kruskal-Wallis tests of performance differences between control, APD+ and APD-subjects on temporal processing tasks.

	Within-channel gap detection	Between-channel gap detection	Sequential auditory TOJ	Overlapping auditory TOJ	Sequential visual TOJ	Overlapping visual TOJ	Coherent motion detection	Transparent motion detection
Difficult	χ^2 = 10.95 p = 0.004	χ^2 = 14.13 p = 0.001	χ^2 = 13.12 p = 0.001	χ^2 = 4.92 p = 0.085	χ^2 = 9.13 p = 0.010	χ^2 = 8.11 p = 0.017	χ^2 = 2.95 p = 0.228	χ^2 = 1.06 p = 0.587
Moderate	χ^2 = 1.21 p = 0.545	χ^2 = 17.34 p < 0.001	χ^2 = 13.98 p = 0.001	χ^2 = 20.43 p < 0.001	χ^2 = 3.74 p = 0.154	χ^2 = 3.33 p = 0.19	χ^2 = 0.49 p = 0.784	χ^2 = 0.59 p = 0.746
Easy	χ2 = 1.92 p = 0.383	χ^2 = 10.46 p = 0.005	χ^2 = 18.32 p < 0.001	χ^2 = 20.71 p < 0.001	χ^2 = 5.21 p = 0.074	χ^2 = 0.41 p = 0.816	χ^2 = 0.54 p = 0.764	χ^2 = 3.71 p = 0.156

Chi squared values (χ2) and significance levels (p) are shown for Kruskal-Wallis tests of the effect of subject group (control, APD+ and APD-) on performance on 3 levels ("difficult", "moderate" and "easy") of each of 8 temporal processing tasks. The Bonferroni-corrected alpha was 0.0063, with 2 degrees of freedom.

Table 3
Correlations between temporal processing and language/ reading performance across all subjects.

	Within-channel gap detection	Between-channel gap detection	Sequential auditory TOJ	Overlapping auditory TOJ	Sequential visual TOJ	Overlapping visual TOJ	Coherent motion detection	Transparent motion detection
Olson phono	r = 0.273 p = 0.022	r = 0.424 p < 0.001	r = 0.350 p = 0.003	r = 0.450 p < 0.001	r = 0.375 p = 0.001	r = 0.322 p = 0.007	r = 0.043 p = 0.722	r = 0.046 p = 0.706
Olson ortho	r = 0.198 p = 0.100	r = 0.429 p < 0.001	r = 0.277 p = 0.020	r = 0.366 p = 0.002	r = 0.321 p = 0.007	r = 0.246 p = 0.040	r = 0.065 p = 0.592	r = 0.114 p = 0.345
CTOPP	r = 0.425 p < 0.001	r = 0.458 p < 0.001	r = 0.483 p < 0.001	r = 0.531 p < 0.001	r = 0.465 p < 0.001	r = 0.365 p = 0.002	r = 0.138 p = 0.255	r = 0.241 p = 0.044
WRAT-3	r = 0.268 p = 0.025	r = 0.494 p < 0.001	r = 0.492 p < 0.001	r = 0.548 p < 0.001	r = 0.493 p < 0.001	r = 0.340 p = 0.004	r = 0.009 p = 0.943	r = 0.089 p = 0.463

Spearman correlation coefficients (r) between temporal processing and language/reading tasks are shown, along with significance level (p). Data are pooled across all subjects (n = 70).

Table 4
Correlations between temporal processing and language/ reading performance in control subjects.

	Within-channel gap detection	Between-channel gap detection	Sequential auditory TOJ	Overlapping auditory TOJ	Sequential visual TOJ	Overlapping visual TOJ	Coherent motion detection	Transparent motion detection
Olson phono	r = 0.308 p = 0.086	r = 0.388 p = 0.028	r = 0.198 p = 0.277	r = 0.346 p = 0.052	r = 0.364 p = 0.041	r = 0.376 p = 0.034	r = -0.254 p = 0.161	r = 0.113 p = 0.539
Olson ortho	r = 0.229 p = 0.207	r = 0.248 p = 0.171	r = 0.186 p = 0.307	r = 0.111 p = 0.545	r = 0.309 p = 0.085	r = 0.125 p = 0.496	r = 0.259 p = 0.152	r = 0.166 p = 0.363
CTOPP	r = 0.264 p = 0.145	r = 0.320 p = 0.074	r = 0.476 p = 0.006	r = 0.503 p = 0.003	r = 0.346 p = 0.052	r = 0.422 p = 0.016	r = 0.047 p = 0.798	r = 0.252 p = 0.164
WRAT-3	r = 0.342 p = 0.056	r = 0.456 p = 0.009	r = 0.469 p = 0.007	r = 0.538 p = 0.001	r = 0.571 p = 0.001	r = 0.162 p = 0.376	r = -0.051 p = 0.780	r = 0.234 p = 0.197

Spearman correlation coefficients (r) between temporal processing and language/reading tasks are shown, along with significance level (p). Data are pooled across learning-impaired subjects (n = 32).

Table 5
Correlations between temporal processing and language/ reading performance in learning-impaired subjects.

	Within-channel gap detection	Between-channel gap detection	Sequential auditory TOJ	Overlapping auditory TOJ	Sequential visual TOJ	Overlapping visual TOJ	Coherent motion detection	Transparent motion detection
Olson phono	r = 0.041 p = 0.812	r = 0.064 p = 0.709	r = 0.149 p = 0.380	r = 0.180 p = 0.286	r = 0.118 p = 0.487	r = 0.118 p = 0.485	r = 0.238 p = 0.156	r = -0.109 p = 0.519
Olson ortho	r = -0.343 p = 0.038	r = -0.018 p = 0.914	r = -0.294 p = 0.077	r = 0.076 p = 0.654	r = -0.029 p = 0.864	r = 0.066 p = 0.700	r = 0.030 p = 0.861	r = 0.051 p = 0.765
CTOPP	r = 0.312 p = 0.060	r = 0.293 p = 0.079	r = 0.170 p = 0.316	r = 0.105 p = 0.535	r = 0.308 p = 0.063	r = 0.079 p = 0.640	r = 0.361 p = 0.028	r = 0.197 p = 0.243
WRAT-3	r = -0.129 p = 0.447	r = 0.061 p = 0.720	r = -0.049 p = 0.771	r = 0.221 p = 0.188	r = 0.163 p = 0.335	r = 0.280 p = 0.094	r = 0.178 p = 0.293	r = 0.001 p = 0.995

Spearman correlation coefficients (r) between temporal processing and language/reading tasks are shown, along with significance level (p). Data are pooled across control subjects (n = 38).

visual sequential TOJ task ($p < 0.05/32$; Table 3). Similarly, individuals who scored higher on the WRAT-3 reading and CTOPP test also scored higher on these three relative timing tasks, as well as the auditory sequential TOJ task. CTOPP scores were also found to correlate positively with within-channel gap detection performance. Performance on the Olson orthographic reading test correlated with only one temporal processing task, namely, the between-channel gap detection. Taken together, these findings indicate that there is a strong association between performance on phonological awareness or reading tasks, and temporal processing tasks that require the relative timing of two or more sensory events.

It is possible that much of the relation between test measures observed in the above analysis can be trivially explained by LI subjects performing more poorly than controls on these language/reading and temporal processing tasks. To test for correlations between temporal processing and language/reading performance beyond this main group effect, we carried out the above Spearman correlations separately for the LI and control subject groups. The results for control subjects are given in Table 4. For this subject group, a significant positive correlation was found between the WRAT-3 reading test scores and two of the TOJ tasks (the auditory overlapping TOJ and the visual sequential TOJ; $p < 0.05/32$). However, no significant correlations were found between the temporal processing and language/reading tasks for the LI subgroup ($p > 0.05/32$; Table 5).

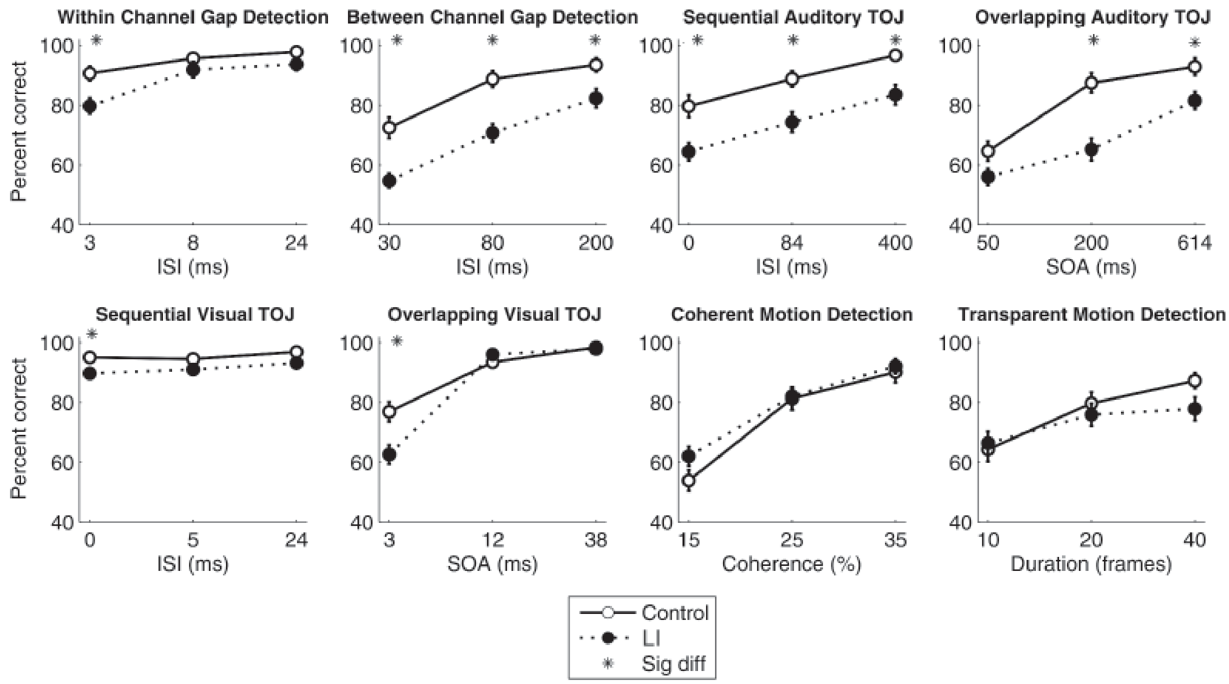
Discussion

Many past studies have shown that individuals with specific language and/or reading impairments perform poorly on several tests of sensory temporal processing (reviewed in Farmer & Klein, 1995) and have abnormal electrophysiological responses to non-verbal, rapidly presented stimuli (Bishop, 2007). However, the timing aspects of tasks used in the literature have varied widely, so it is unclear whether the underlying neural pathology that leads to language and reading impairments is one of neural conduction velocities (Livingstone, Rosen, Drislane, & Galaburda, 1991), neural refractoriness (Gilley et al., 2005), phase-locking to periodic sounds (Stefanatos, Green, & Ratcliff, 1989), perceptual integration timing (Hari & Kiesila, 1996; Tallal & Newcombe, 1978), perceptual processing efficiency (G. T. Hill & Raymond, 2002; P. R. Hill, Hartley, Glasberg, Moore, & Moore, 2004), or a combination of these and possibly other factors. To further confuse the issue, a number of studies have failed to replicate many of the sensory temporal processing impairments in dyslexic readers (McArthur & Bishop, 2001), which may reflect the heterogeneity of neural etiologies across the dyslexic population. Nevertheless, the evidence indicates that some temporal aspects of perceptual decision-making are likely to play a more crucial role in language and reading development than others, and it is important that we determine how these temporal processes can be better defined.

To this end, we have previously shown that, in unselected readers, performance on perceptual tasks that require the relative timing of two or more events is highly correlated with phonological awareness and phonological aspects of reading (Walker et al., 2006). In the present study, we expanded on this previous work using the same battery of psychophysical tasks (which probe a number of quite different temporal processes) to compare the basic perceptual performance of children with learning impairments to age-matched controls. The LI subjects performed more poorly than controls on reading and phonological awareness tasks, but not on the Token Test. We note that the Token Test is often used as a screening tool for aphasia, and only one of the children in this study failed the test.

A major finding of the present study was that the participants with LI were also found to be impaired on several of our temporal processing tasks. The LI participants struggled with tasks that required the relative timing of two temporally proximate cues, especially in the auditory domain. LI subjects were also impaired on relative timing tasks in the visual domain, but only when these tasks were presented at the most challenging level. The scores of both control and LI subject groups were near ceiling on the visual TOJ tasks,

Figure 2: Temporal processing performance of control and learning-impaired subject groups. Group mean performance on the temporal processing tasks, plotted separately for control and learning-impaired subject groups. Upper panels depict scores for the auditory tasks, with task difficulty as the independent variable for each plot. Lower panels show data for the visual tasks, plotted in the same manner. Error bars are standard errors of the mean and asterisks indicate that group means were significantly different at $p < 0.05/8$.

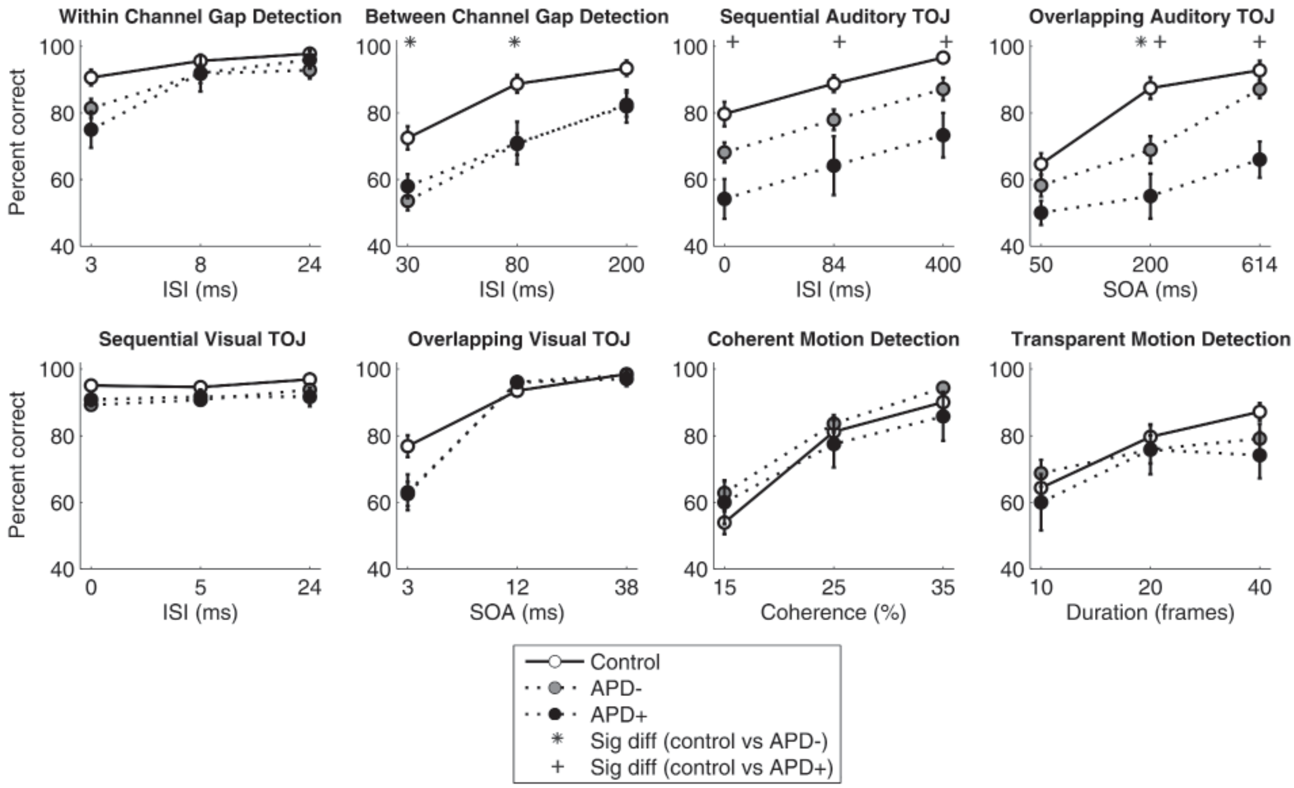


so it is possible that more robust impairments would be observed for LI subjects on these tasks if they were more perceptually difficult, for instance, by shortening the duration of the visual stimulus. This remains to be determined, and the same caveat should be considered for the results of the within-channel gap detection task. A modest impairment in performance was found on the within-channel gap detection task, but only when the gap to be detected was less than 8 ms in duration. Finally, no significant impairment was found on our motion detection tasks, for which performance was not at ceiling. These results are consistent with a special status of relative timing operations as a perceptual correlate of reading and language performance. The temporal processing correlates of reading performance are heterogeneous in the perceptual operations they tap. One qualification to this line of argument is that within-channel gap detection performance may have a steeper developmental trajectory than performance on the relative timing tasks (after Hautus, Setchell, Waldie, & Kirk, 2003; Walker et al., 2006). In our own earlier study, normal children as young as 9 to 10 years were already close to ceiling performance on the within-channel task, while they continued to improve through early teenage years for the between-channel task (Walker et al., 2006). Therefore, a temporal processing "disorder" might simply be a developmental delay from which the child eventually recovers. By the time he or she does so, however, the child may have learned to avoid reading and language tasks because these were labour-intensive and frustrating. It may be for this reason that some older children show impaired language or reading at an age at which they do not exhibit a concurrent temporal processing problem. By the same token, there may be a subset of children for whom the reading and language deficit may be remediated by training when the temporal processing mechanisms have matured.

Several studies have suggested that auditory processing disorders, as defined by standard clinical testing, can be associated with or contribute to the development of generalized learning disabilities (Pinheiro, 1977; Willeford, 1977), as well as more specific reading, language, and attention deficit disorders (Cacace & McFarland, 1998). However, it is unclear whether the type of auditory processing disorder that leads to a positive APD diagnosis is equivalent to the auditory temporal processes that have been shown to relate to reading and language performance. Furthermore, studies of APD usually only test sensory processing in the auditory domain, so the existence of a multimodal processing disorder is not ruled out.

In the present study, LI subjects completed a standard test of APD in addition to our multi-modal temporal processing battery. We found that the rank order of group performance on phonological awareness and reading tests followed a consistent pattern. The mean score of the LI group was lower than age-matched controls, and the group of LI subjects with a positive APD diagnosis performed more

Figure 3: Temporal processing performance of control, APD-, and APD+ subject groups. Same data set as shown in Figure 2, but with data from the learning-impaired subjects shown separately for those diagnostically negative and positive for APD. Details are as for Figure 2. Significant group mean differences (p < 0.05/8) between control and APD- (asterisks) subjects and control and APD+ (crosses) subjects are indicated.able 1: Kruskal-Wallis tests of performance differences between control and LI subjects on temporal processing tasks.



poorly than LI subjects without APD. These preliminary data suggest that APD may not be necessary to cause language and reading impairments within the LI population (see also Bishop et al., 1999). Nevertheless, APD may further impair reading performance in individuals with LI. Similarly, on the auditory temporal order judgment tasks, the mean group performance of LI subjects with APD was lower than that of LI subjects without APD, although this effect was usually not statistically significant. A surprising finding was that LI subjects without APD were significantly impaired (compared to controls) on the between-channel gap detection task, while LI subjects with APD were not impaired on this task. This result is somewhat at variance with that of Phillips et al. (2010), who showed that children with APD performed more poorly on the between-channel task than children without this diagnosis. These contrary findings may simply reflect the use of more sophisticated adaptive psychophysical methods in the latter study.

We did not see evidence of APD+ subjects performing more poorly on visual temporal processing tasks than APD- subjects. This suggests that the presence of APD in LI subjects may further compromise an already impaired temporal processing in the auditory domain. However, learning-impaired subjects with and without APD performed more poorly on tests of auditory and visual TOJ, so the sensory disorder in these APD+ subjects cannot be described as a strictly auditory impairment. Current tests of APD that do not assess perceptual processes in sensory systems beyond the auditory system may therefore be inadequate to fully describe the sensory deficits of some individuals, as previously argued by Cacace and McFarland (2005). Interestingly, the APD+ and APD- groups did not differ in their performance on any visual task in the battery (Figure 3). Thus, while APD might coexist with visual processing problems in LI (Figure 2), APD does not appear to impact the child's visual processing performance any further. This finding underlines the modality specificity of APD.

The APD diagnostic battery included a Random Gap Detection Test that was similar to the within-channel gap detection task used in our study. None of the LI subjects failed the Random Gap Detection Test of the APD battery, so the trend for APD+ subjects to perform worse on gap detection compared to subjects without this label is not simply a consequence of the tests used to arrive at the APD diagnosis in the first place. The other test of temporal processing included in the APD battery is the Pitch Pattern Sequence Test, which is similar to our auditory sequential TOJ task (although in the later case, stimuli are more closely spaced in time and are presented only in pairs). Twenty of the 38 tested subjects failed the Pitch Pattern Sequence Test, and nine of these same subjects met the criteria for an APD diagnosis. However, the APD observed in these nine subjects was not limited to auditory temporal processing. Each of these subjects also failed at least four of the six other tests for APD, including tests of dichotic listening. The data further demonstrate the extent of the temporal processing deficit experienced by children with APD, even when they pass the standard test of auditory gap detection included in the APD testing battery.

This brings us to the second major finding of the present study. If auditory temporal processing development plays an important role in language and reading proficiency, then one might expect these two measures to be correlated within individuals. Across all subjects in our study, we found a correlation of phonological awareness and reading performance with tasks of relative timing judgments, particularly in the auditory domain. The correlation between reading and temporal order judgements persisted within our group of control subjects. Other studies have also found associations between temporal processing and reading tasks within unimpaired or unselected readers (Au & Lovegrove, 2001a, 2001b; Talcott et al., 2002; Walker et al., 2006; Witton et al., 1998), but correlations between these measures in dyslexic readers have been less consistent (Ahissar, Protopapas, Reid, & Merzenich, 2000; Rosen, 2003; Witton et al., 1998). In the present study, we did not find evidence that temporal processing measures correlated with reading or phonological awareness scores in the children with LI. This finding is all the more puzzling because the controls demonstrated consistent correlations between reading and temporal processing measures. Inspection of the scatter plots relating the two measures revealed wide variance in scores along both measures, so the statistically insignificant correlations in the LI group cannot be explained by a lack of variance. The lack of correlations found between temporal processing and language/reading tasks in both subgroups (Tables 4 and 5), compared to the combined group of subjects (Table 3), may also result from the fact that the subject size is necessarily larger in the later. Klein (2002) argues that reading is a phylogenetically recent skill that builds on neural and cognitive mechanisms that have evolved for other purposes. Competent temporal processing skills may be a requirement for the optimal development of reading and language skills. In the presence of poor temporal processing, the child must compensate using heterogeneous and suboptimal perceptual or cognitive strategies to perform language or reading tasks. For the present study, this heterogeneity may have been particularly marked because of the unselected nature of the LI group. The combination of heterogeneous and suboptimal processing strategies in the LI group would result in relatively low absolute scores, and explain the poor correlation of perceptual processing performance and language performance.

Finally, it is possible that LI and APD on the one hand, and performance on temporal processing tasks on the other, are all influenced by a third variable. The most obvious candidate for such a third variable correlation is general cognition. However, it has been shown empirically that attentional and other cognitive factors play only a minor role in the tasks required for diagnosis of APD or dyslexia (Illadou et al., 2009; Sharma et al., 2009; Cohen-Mimran and Sapier, 2009; Dawes et al., 2009). Tallal and Piercy (1973) demonstrated differential performance on an auditory temporal ordering task ("repetition test") in IQ-matched normal and language-learning impaired children. This task was very similar to our own sequential temporal order judgement task. These data do not support a view that temporal processing performance and reading performance are each mediated by a third (cognitive) factor.

The present study provides further evidence for relative timing deficits in a clinical group with impoverished reading and phonological awareness performance. The results suggest that an APD may impact reading, phonological awareness and relative timing judgments in individuals with LI. Based on our data alone, it remains impossible to tell whether a deficit in temporal processing judgments may lead to impaired language and reading performance, or vice versa. This pivotal question should be addressed by further studies by adopting a longitudinal approach. We have shown that APD does not always present as a specific auditory disorder but rather can co-exist with more subtle impairments in the relative timing of rapid visual stimuli.

Acknowledgments

This research was supported by grants from the Hearing Foundation of Canada, the Natural Sciences and Engineering Research Council of Canada (NSERC), and the Canadian Language and Literacy Research Network (CLLRNet). Additional support for DPP and KMMW was provided by the Killam Trust. Programming and technical support was provided by Susan E. Hall. We express special thanks to the children who participated in this study, and to their parents and teachers, without whose cooperation this study could not have been completed. We also thank three anonymous reviewers for their very helpful comments on an earlier version of this manuscript.

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Received: October 7, 2009

Accepted: June 14, 2010

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