Visual and Auditory Temporal Processing and Early Reading Development

Michelle Hood* and Elizabeth Conlon

School of Applied Psychology, Applied Cognitive Neuroscience Research Centre, Griffith University, Queensland, Australia

This study investigated the ability of temporal processing measures obtained before school entry to predict early reading development in an unselected sample of 125 children (68 males, 57 females). Visual and auditory temporal order judgement (TOJ) tasks measured at Preschool (mean age 5.36 years) significantly predicted letter and word identification (accuracy) and reading rate (fluency) in early Grade 1 (mean age 5.94 years), even after the effects of age, environment, memory, attention, nonverbal ability, and speech/language problems were accounted for. There were no significant differences in the overall variance accounted for in reading between TOJ measures taken before or after reading had emerged. Both Preschool and Grade 1 measures of auditory TOJ accounted for significant independent variance in reading. However, only visual TOJ performance measured at Grade 1 accounted for unique variance in reading rate. This was discussed in terms of developmental changes in the role of visual temporal processing as reading develops. Reliability of the temporal measures from Preschool to Grade 1 was moderate. The results showed that measures of visual and auditory temporal processing obtained close to school-entry would be a useful addition to predicting risk of early reading difficulties.

Keywords: temporal order judgement; reading; dyslexia; visual temporal processing; auditory temporal processing; reading development

*Correspondence to: Michelle Hood, School of Applied Psychology, Griffith University, Gold Coast, PMB 50 Gold Coast Mail Centre, 9726, Australia. Tel.: +61-7-5552-8211; fax: +61-7-5552-8291; e-mail: michelle.hood@griffith.edu.au; Contract/grant sponsor: School of Applied Psychology, Griffith University; Contract/grant sponsor: Learning Disabilities Action Network

Published online in Wiley InterScience (www.interscience.wiley.com). DOI: 10.1002/dys.273

INTRODUCTION

Learning to read is a seemingly simple process for most children. However, 5–17% of children have developmental reading disability or dyslexia (Shaywitz, Shaywitz, Fletcher, & Escobar, 1990). The temporal processing deficit hypothesis of dyslexia focuses on the causal role of fundamental auditory and visual perceptual deficits, which have been found in children and adults with dyslexia (for reviews of this hypothesis see Farmer & Klein, 1995; Habib, 2000). Ahissar, Protopapas, Reid, and Merzenich (2000) noted greater auditory perceptual deficits in tasks that involved processing of brief, rapidly presented stimuli. Hari and Renvall (2001) noted similar visual deficits. Neurologically, these deficits have been associated with impairments in the magnocellular retino-cortical visual system (Eden *et al.*, 1996; Facoetti & Molteni, 2001; Livingstone, Rosen, Drislane, & Galaburda, 1991) and in the magnocellular layers of the medial geniculate nucleus in the auditory system (Galaburda, Menard, & Rosen, 1994). These magnocellular impairments may develop *in utero* (Galaburda, Sherman, Rosen, Aboitiz, & Geschwind, 1985; Stein, 2001a). The magnocellular system responds to rapidly changing stimuli, so impairments would result in temporal processing deficits.

Between reader group differences have been found on temporal order judgement (TOJ) tasks, which involve judging the order of two rapidly presented stimuli. Stimuli may be either visual or auditory, and either verbal or nonverbal. Using an auditory TOJ task, Tallal (1980) initially showed that a group of dyslexic children (8–12 year olds) were significantly less accurate than a control group when inter-stimulus intervals (ISIs) were short (8–305 ms) but did not differ from the controls when ISIs were long (428 ms). Others replicated these results (de Martino, Espesser, Rey, & Habib, 2001; Farmer & Klein, 1993; Reed, 1989; Rey, de Martino, Espesser, & Habib, 2002). Brannan and Williams (1988) reported similar group differences on visual TOJ tasks in 8–12 year olds. The minimum ISI required to correctly judge the order accounted for up to 44% of the variance in reading level. These findings supported the hypothesis of a deficit in processing rapidly presented stimuli.

However, results are mixed. Some studies found no significant group differences on auditory TOJ tasks (Nittrouer, 1999) or on visual TOJ tasks (Farmer & Klein, 1993; Reed, 1989). Other studies found significant between reader group differences on auditory TOJ performance at both short and long ISIs (Bretherton & Holmes, 2003; Cestnick, 2001; Cestnick & Jerger, 2000; Waber *et al.*, 2001) or even only at long ISIs (Share, Jorm, Maclean, & Matthews, 2002). This contradicted the hypothesis of a specific impairment in processing rapidly presented stimuli. In some studies, the auditory TOJ deficits only occurred in children with both reading disability and specific language disability (SLD; Heath, Hogben, & Clark, 1999; Stark, Tallal, & McCauley, 1988; Tallal & Stark, 1982), which raised questions over whether these deficits were related to reading or to language disability.

The inconsistency of results may be due to the small samples and selected groups used. Small samples limit the generalizability of results, to both the population and to a given individual (Talcott *et al.*, 2002). Even when studies found significant group differences, the entire dyslexic group did not perform less accurately than the control group. In Tallal's (1980) study, for example, only

45% of dyslexic group had lower scores than the control group. Criteria for selecting dyslexic or poor readers differed between studies, making comparisons difficult and possibly explaining the mixed findings (Breier, Gray, Fletcher, Foorman, & Klaas, 2002; Talcott *et al.*, 2002). Selection could introduce potential confounds because conditions such as SLD and attention-deficit hyperactivity disorder (ADHD) show high co-morbidity with dyslexia (Breier, Gray, Fletcher, Foorman, & Klaas, 2002). Presence or absence of these confounds could explain differing results.

A normative approach with unselected samples of readers can overcome these methodological issues. Reading ability is a continuously distributed variable in which dyslexia represents the lower tail of the normal distribution, rather than constituting a separate population (Shaywitz, Escobar, Shaywitz, Fletcher, & Makuch, 1992). Temporal processing ability was also found to be continuously distributed within the population (Cornelissen, Richardson, Mason, Fowler, & Stein, 1995; Talcott *et al.*, 2000). It makes sense, therefore, to investigate the relationship between temporal processing and reading across the normal range of abilities.

Very few studies have used a normative approach with children. Auditory TOJ accuracy (collapsed across a range of short ISIs) was significantly related to reading ability in an unselected sample of children (6–13 years old, Marshall, Snowling, & Bailey, 2001). No normative studies have used visual TOJ tasks. However, performance on other visual temporal processing tasks (coherent motion threshold and contrast sensitivity) was significantly related to different components of reading in children and adolescents with a wide range of reading abilities (Cornelissen, Hansen, Hutton, Evangelinou, & Stein, 1998; Olson & Datta, 2002). Talcott *et al.* (2000, 2002) extended these findings to show that performance on both auditory (frequency modulation detection) and visual (motion coherence) temporal processing tasks accounted for small, but significant, amounts of variance in reading in unselected samples of children (7–11 years), after the effects of age and nonverbal ability were controlled for. Further normative studies into the relationship between perceptual deficits and reading ability are required (Wright, Bowen, & Zecker, 2000).

Several questions remain unanswered. Talcott *et al.* (2000, 2002) did not report the combined effect of performance on their auditory and visual tasks so the extent to which these tasks accounted for overlapping variance in reading skills is unknown. In addition, existing studies have all used older children. Longitudinal predictive studies have been called for to clarify the relationship between temporal processing and reading ability in beginner readers (Farmer & Klein, 1995; Ramus, 2004; Stein, 2001b). There is only one reported longitudinal study. After controlling for vocabulary and memory, Lovegrove, Slaghuis, Bowling, Nelson, and Geeves (1986) showed that contrast sensitivity function measured at kindergarten (6 years) accounted for significant variance in reading ability 2 years later.

The current study addressed three questions, using a longitudinal design and a normative sample. The first question concerned the predictive relationships between Preschool auditory and visual TOJ performance and reading ability in the first 6 months of school. If temporal processing impairments are due to prenatal neurological changes, they should be identifiable before reading develops. If they are causally related to reading, pre-existing temporal processing abilities should be predictive of subsequent reading abilities. A range of control measures, including attention and speech/language problems, were included to determine if these could explain the relationship between temporal processing and reading. The second question investigated developmental factors in the relationship between TOJ performance and reading ability. The amount of variance in Grade 1 reading accounted for by TOJ performance measured at Preschool was compared to that accounted for by TOJ performance measured at Grade 1. Of interest was whether the emergence of reading in between these two measurement times significantly changed the relationship between temporal processing and reading. The third question concerned the reliability or stability of the temporal processing measures across the developmental period during which reading emerges. If the measures are both reliable and predictive of early reading ability, each child's location within the distributions of performance on these measures may provide an additional indicator to strengthen early assessment of risk for reading difficulties.

METHOD

Participants

One hundred and sixty children, whose main language was English, were recruited from three local Preschools in 2000 and 2001 (Preschool is the non-compulsory year before school entry, during which there is no formal literacy instruction). Two cohorts from three schools were tested to reduce internal validity threats, such as history. Children were excluded if they had known developmental disorders, neurological or intellectual problems that might constitute biological risk factors for learning problems (Fletcher *et al.*, 2002). Children were also excluded if they were already reading at Preschool. 'Readers' were those whose raw score on the Letter and Word Identification subtest of the Woodcock diagnostic reading battery (WDRB; Woodcock, 1997) was above 17, indicating a small sight word vocabulary.

This resulted in 144 participants (78 males, 66 females) at Preschool. Mean age at mid-testing was 5.36 years (*S.D.* = 0.31 years). Of these, 125 (68 males; 57 females) were available for re-testing in Grade 1 (mean age mid-testing 5.94 years, *S.D.* = 0.31). All children were of normal intelligence (estimated from their score on Raven's Coloured Progressive Matrices; Raven, Court, & Raven, 1986) and had normal or corrected to normal visual acuity and normal hearing. The sample included 30 children whose parents reported speech/language problems. Of these, nine (4 males, 5 females) had seen a speech pathologist.

Materials and Stimuli

Temporal processing tasks

Auditory temporal order judgement (ATOJ). A simplified version of Tallal's (1980) TOJ task, the Sound Order sub-test of the Dyslexia Early Screening Test (DEST), was used (Fawcett & Nicolson, 1995; Nicolson & Fawcett, 1996). The DEST was designed for children aged 4.50–6.42 years. A low tone (duck quack, 166 Hz) and a high tone (mouse squeak, 1430 Hz) were presented in random order, separated by varying ISIs, on an audiotape played on a Sony TCM 939 portable tape player. Stimulus duration was 155 ms and ISIs were 8, 15, 30, 60, 150, and 300 ms. There were four identification and four practice trials, followed by two catch trials (947 ms ISI) and 14 experimental trials (2–3 trials per ISI). The catch trials detected poor vigilance or random responding. The required response was the sound that occurred first. Reported 1-week test–retest reliability was 0.64 ($N = 26$; Nicholson & Fawcett, 1996). The dependent measure was the total number of trials, collapsed across all short ISIs, on which the child correctly identified the first sound (accuracy). This measure was used previously with children and adolescents in both between groups and normative designs (Farmer & Klein, 1993; Marshall, Snowling, & Bailey, 2001; Share *et al.*, 2002).

Visual temporal order judgment (VTOJ). This task was based on the methodology of Reed (1989). The task used nonverbal stimuli because they are purer tests of visual deficits than verbal stimuli, which involve greater phonological processing (Vellutino, 1979). The task was presented on an IBM compatible PC with a 17-in monitor and a screen refresh rate of 18 ms. A 500 ms high-frequency auditory tone cue preceded each trial. A central white fixation cross appeared on a grey background (space average luminance 15 cd/m^2) for an initial 500 ms and remained visible throughout each trial. Stimuli were white circles, subtending 1° visual angle. The first stimulus was randomly presented to either the left or right of fixation. Stimulus duration was 83 ms and ISIs of 55, 75, 100, 150, and 200 ms separated presentation of the first and second stimulus circle. The second stimulus appeared on the opposite side of the fixation cross. The proximal distance of each stimulus to central fixation subtended 2° visual angle.

There were four identification and four practice trials followed by a 40 experimental trials (eight trials per ISI, half with initial right presentation and half with initial left presentation). Eight catch trials, on which only a single stimulus appeared, were interspersed randomly among the experimental trials to detect poor vigilance or random responding.

To be consistent with the auditory TOJ task, pictures of a duck and a mouse were attached to opposite sides of the computer screen on a black surrounding mask. This identified the side of the computer on which the circle appeared. The required response was whose circle appeared first—the duck's or the mouse's. Acceptable responses were verbal or motor (pointing). The experimenter entered the responses via the keyboard. The dependent measure was the number of trials, collapsed across ISI, on which the response was correct (accuracy). This was consistent with the Auditory TOJ and was used previously (Farmer & Klein, 1993).

Control variables

Memory (MEM). The Digit Span Forward subtest from the DEST was used. The score was number of correct trials. Two trials were presented at each level of digits, beginning with two digits. One-week test–retest reliability was 0.63 (Nicolson & Fawcett, 1996).

Early home reading environment (ENV). A parent questionnaire asked about the number of times per week the child was read to, frequency of parental teaching of reading/writing/alphabet (1 =never; 5 =very often), and the number of children's books in the home. Parents also completed a children's titles checklist (CTC). This included 20 popular age-appropriate children's book titles and 10 foils. Titles checklists measure print exposure and predict reading ability (Cipielewski & Stanovich, 1992; McBride-Chang, Manis, Seidenberg, Custodio, & Doi, 1993). The list was derived from Angus and Robertson's 100 all-time favourite children's books (1999) and previously used CTCs (Cunningham & Stanovich, 1993; Senechal, LeFevre, Thomas, & Daley, 1998). The CTC score was the number of real titles checked minus the number of foils checked. Based on loadings in a principle components analysis, a composite measure of early home reading environment score was calculated from the sum of the questionnaire items plus the CTC score. A higher score indicated a more enriched home literacy environment.

Attentional vigilance (VIG). There is evidence that differences in attentional vigilance may influence temporal processing accuracy (Davis, Castles, McAnally, & Gray, 2001; Stuart, McAnally, & Castles, 2001; Talcott *et al.*, 2002). Based on loadings in a principle components analysis, a composite measure of vigilance was constructed from the sum of scores on the catch trials on the visual TOJ (single stimulus presentation only) and auditory TOJ tasks (947 ms ISI) and on the Guide to the Assessment of Test Session Behaviour (GATSB; Glutting & Oakland, 1993). A higher score indicated better attentional vigilance.

Nonverbal ability (MAT). This was measured using Raven's Coloured Progressive Matrices (Raven *et al.*, 1986). Reported internal consistency for a Queensland sample (mean age 5.5 years) was high, Cronbach's alpha = 0.80.

Grade 1 reading measures

Single letter and word reading accuracy (LetterWord Id). This was measured using the Letter Word Identification subtest of the WDRB (Woodcock, 1997). This is a graded list, beginning with selected letters (upper and lower case) and continuing with words of increasing difficulty. Score was the number of correct items identified. Reliability is 0.94 for 5–18 year olds.

Single word fluency (reading rate). Children read as many words as possible by sight in 1 min (timed with a stopwatch) from a list of 120 words taken from the Dolch sight word lists (Dolch, 1936). These words are the highest frequency English words and corresponded to the classroom sight word lists. Words were typed down the page in three columns in Berlin Sans FB font, size 20. This font produced letters most like the script that the children were learning. The dependent measure was the number of words correctly identified in 1 min.

Procedure

This research had Griffith University Research Ethics Committee clearance, which adheres to the guidelines of the National Health and Medical Research Council of Australia. Testing occurred in the IV term of Preschool (October–December) and again, 6–8 months later, in the II term of Grade 1 (April–June). At

Preschool, informed parent consent and parent questionnaires were completed and children were screened for pre-existing reading ability. Eligible children were tested on the TOJ tasks in random order as part of a larger battery of tests. At Grade 1, the order of testing was LetterWord Id followed by the TOJ tasks (in random order as part of the larger battery) and lastly, reading rate. Individual testing was conducted in a quiet room at the school. During each phase of testing, the complete battery required approximately seven sessions, of around 20 min each, to complete. If a child was inattentive or uncooperative, the testing session was ended. Children were thanked with stickers and/or colouring sheets at the end of each session.

Standardized testing procedures were followed for the Auditory TOJ, Memory, Matrices, and LetterWord Id tests. Instructions on the reading rate task were to read the words as quickly as possible and to proceed to the next word if they did not immediately know a word. Children were told not to sound words out.

For the visual TOJ task, children were seated 57 cm from the screen. They were initially trained to fixate on the central cross. On both TOJ tasks, children first completed identification trials (single stimulus presentation) to ensure they could correctly identify the stimuli. They then completed practice trials (two-stimulus sequences). Feedback regarding accuracy was given on these trials and they were repeated, if necessary. Few children required repeat practice. The response format was a two alternate forced choice. Children gave their best guess if they were unsure on a trial. Before each trial on the auditory TOJ, participants were verbally cued to attend for the sounds. On the visual TOJ task, the auditory tone, which preceded each trial, cued participants to fixate on the central cross and to attend for the circles. The experimenter initiated each trial after ensuring that the child was correctly seated and was fixated on the cross. Visual TOJ testing took place in two sessions on different days, with two blocks (20 experimental and eight catch trials each) per session.

RESULTS

Participants were excluded if they had missing data. Table 1 displays descriptive statistics for the sample.

Prediction of Grade 1 Reading by Preschool TOJ Measures

This was evaluated using hierarchical multiple regression analyses. The DVs were Grade 1 letter word identification (LetterWord Id) and reading rate. A square root transformation normalized the distribution of scores on reading rate. The scores on attentional vigilance and on auditory TOJ were reflected and log transformed to achieve normality. Speech/language problems was a categorical variable, dummy-coded as 1 = problems reported and 0 = no problems reported. All of the other assumptions of the analyses were met.

Table 2 presents Pearson bivariate correlations between the measures. Of the control measures, age, attentional vigilance (VIG), and nonverbal ability (MAT) showed significant weak correlations with Grade 1 LetterWord Id. Being older, being more vigilant, and having higher nonverbal ability were associated with higher scores on LetterWord Id. The correlation between memory (MEM) and

Table 1. Means (SD, range) and maximum score (if relevant) on predictor and outcome measures for whole sample ($N = 123$)

	Year	
Measure	Preschool	Grade 1
ENV (max.=57)	32.95 (6.77; 19–50)	
VIG (max.=37)	33.45 (4.05; 21–37)	
MEM	5.15 (1.42; 2–9)	
MAT-std. score	108.24 (10.47; 81–135)	
ATOJ (max.=14)	10.83 (2.37; 4–14)	12.10 (1.79; 7–14)
VTOJ (max.=40)	26.63 (5.99; 9–39)	30.89 (5.64; 15–40)
LetterWord Id	10.24 (3.00; 4–17)*	14.50 (3.48; 7–28)
Reading rate (max.=120)		17.78 (14.41; 0–78)

ENV, Home literacy environment; VIG, composite Attentional Vigilance score; MEM, DEST Digit Span; MAT, Raven's Coloured Progressive matrices, ATOJ, Auditory TOJ; VTOJ, Visual TOJ.
*Max. allowed=17.

LetterWord Id approached significance ($p = 0.053$). Age, home environment (ENV), VIG, and MAT were significantly weakly correlated with Grade 1 reading rate. Higher scores on these control measures were associated with faster reading rate. The control measures also showed significant weak to moderate correlations with the TOJ measures, such that higher scores were associated with more accurate temporal order judgement. The auditory and visual TOJ measures showed significant moderate correlations with each other. There was a moderate positive linear relationship between the TOJ measures and the reading measures, such that more accurate temporal processing was associated with higher scores on both reading measures. There was a strong positive linear relationship between the reading measures.

Prediction of Grade 1 letter–word identification

In each hierarchical regression analysis, the control measures were entered at Step 1, followed by the speech/language problem variable at Step 2. The temporal processing measures were entered at Step 3. Table 3 presents the results of the regression models.

At Step 1, the control measures (Age, ENV, VIG, MEM, and MAT) accounted for 17.00% of the variance in LetterWord Id, $F(5, 116) = 4.75$, $p = 0.001$. Squared semi-partial correlations showed that AGE and VIG both accounted for significant independent amounts of variance in letter word identification, accounting for 3.46% and 6.15% of the variance, respectively. The addition of the speech/language variable at Step 2 did not result in a significant increase in the amount of variance accounted for, R^2 change=2.40%, $F(1, 115) = 3.37$, $p = 0.069$. The squared semi-partial correlation at Step 3 showed that the TOJ measures accounted for an additional 14.00% of the variance, $F(2, 113) = 11.92$, $p < 0.0001$. Only Preschool ATOJ made a significant independent contribution, accounting for 11.49% of the variance in LetterWord Id. See Table 3a.

Prediction of Grade 1 reading rate

At Step 1 in this analysis, the control measures accounted for 16.70% of the variance in reading rate, $F(5, 116) = 4.66$, $p = 0.001$. Attentional vigilance (VIG)

Table 2. Bivariate correlations

	AGE	ENV	VIG	MEM	MAT	PreATOJ	1ATOJ	PreVTOJ	1VTOJ	LettWord Id	ReadRate
AGE	1.00										
ENV	0.13	1.00									
VIG	−0.13	−0.19*	1.00								
MEM	0.09	0.05	−0.14	1.00							
MAT	0.23*	0.22*	−0.18*	0.18	1.00						
PreATOJ	−0.25**	−0.12	0.25	−0.32**	−0.31**	1.00					
1ATOJ	−0.12	−0.15	0.24**	−0.36**	−0.44**	0.50**	1.00				
PreVTOJ	0.21*	0.24*	−0.34**	0.20*	0.44**	−0.37**	−0.33**	1.00			
1VTOJ	0.00	0.14	−0.26**	0.18*	0.44**	−0.38**	−0.40**	0.54**	1.00		
LettWordId	0.21*	0.14	−0.33**	0.17	0.19*	−0.46**	−0.33**	0.26**	0.36**	1.00	
ReadRate	0.18*	0.20*	−0.34**	0.12	0.20*	−0.40**	−0.37**	0.31**	0.33**	0.84**	1.00

PreATOJ, Preschool auditory TOJ; 1ATOJ, Grade 1 Auditory TOJ; PreVTOJ, Preschool Visual TOJ; 1VTOJ, Grade 1 VISTOJ.
N.B. PreATOJ, 1ATOJ, and VIG were reflected and log transformed so correlations are negative. ReadRate was square root transformed.
*$p < 0.05$.
**$p < 0.01$.

Table 3. Hierarchical regression analyses for variables predicting Grade 1 LetterWord Id and Reading rate ($N = 123$)

		Grade 1 LetterWord Id (DV)					
		(a) Preschool Temporal Measures			(c) Grade 1 Temporal Measures		
Variable		B (*SE* B)	β	*p*	B (*SE* B)	β	*p*
1.	AGE	2.05 (0.93)	0.19	0.03			
	ENV	0.04 (0.05)	0.08	0.343			
	MEM	0.24 (0.21)	0.10	0.251			
	VIG	−3.11 (1.06)	−0.26	0.004			
	MAT	0.06 (0.07)	0.07	0.434			
2.	Speech[a]	−1.40 (0.76)	−0.16	0.069			
3.	ATOJ	−6.21 (1.41)	−0.39	<0.0001	−3.77 (1.73)	−0.21	0.031
	VTOJ	0.08 (0.05)	0.13	0.15	0.17 (0.06)	0.28	0.004
		Grade 1 Reading Rate (DV)					
		(b) Preschool Temporal Measures			(d) Grade 1 Temporal Measures		
Variable		B (*SE* B)	β	*p*	B (*SE* B)	β	*p*
1.	AGE	0.74 (0.47)	0.14	0.119			
	ENV	0.03 (0.02)	0.11	0.197			
	MEM	0.05 (0.11)	0.04	0.612			
	VIG	−1.73 (0.53)	−0.29	0.002			
	MAT	0.03 (0.04)	0.08	0.36			
2.	Speech[a]	−0.91 (0.38)	−0.21	0.018			
3.	ATOJ	−2.32 (0.73)	−0.29	0.002	−2.50 (0.86)	−0.28	0.004
	VTOJ	0.03 (0.03)	0.11	0.271	0.06 (0.03)	0.18	0.055

[a]Speech, dummy coded variable; 0, no speech/language problems; 1, speech/language problems.
N.B. Step 1 results are same for models a & c and b & d.

made the only significant independent contribution, accounting for 7.56% of the variance. At Step 2, the squared semi-partial correlation showed that an additional 4.00% of the variance was accounted for by the presence of speech/language problems, $F(1,\ 115) = 5.77$, $p = 0.018$. The regression coefficient (B; Table 3b) showed that slower reading rate was predicted by the presence of speech/language problems. At Step 3, an additional 8.00% of the variance in Grade 1 reading rate was accounted for by inclusion of the TOJ measures, $F(2{,}113) = 6.30$, $p = 0.003$. Preschool ATOJ independently accounted for 6.40% of the variance, which was significant. See Table 3b.

Prediction Grade 1 Reading by Grade 1 TOJ Measures

A second set of hierarchical multiple regression analyses was conducted using the TOJ performance measured at Grade 1 at Step 3. The same control measures were entered at Steps 1 and 2 (so the results remained unchanged and would not be repeated here). By keeping the variables entered at Steps 1 and 2 constant across all regression analyses, the amount of additional variance accounted for by the Grade 1 TOJ measures at Step 3 could be directly compared to the amount of additional variance accounted for by the Preschool TOJ measures at Step 3. This allowed developmental changes in the relationship of the TOJ measures and reading to be examined. Grade 1 ATOJ scores were reflected and log transformed to reduce negative skew and normalize the distribution. All of the other assumptions were met.

Prediction of Grade 1 letter–word identification

At step 3, the squared semi-partial correlation showed that the Grade 1 TOJ measures accounted for an additional 10.50% of the variance in Grade 1 LetterWord Id, $F(2, 113) = 8.00$, $p = 0.001$. Both Grade 1 TOJ measures accounted for significant independent components of the variance, 2.96% by ATOJ and 5.24% by VTOJ. See Table 3c.

Prediction of Grade 1 reading rate

At step 3, the squared semi-partial correlations showed that the Grade 1 TOJ measures accounted for an additional 9.10% of the variance in Grade 1 Reading Rate, $F(2, 113) = 7.37$, $p = 0.001$. Grade 1 ATOJ independently accounted for 5.24% of the variance, which was significant. Grade 1 VTOJ independently accounted for 2.34% of the variance, but this failed to reach significance, $p = 0.055$. See Table 3d.

Comparison of Preschool and Grade 1 temporal processing measures in predicting Grade 1 reading

Steiger's (1980) z test for comparing elements of a correlation matrix was used to determine whether the TOJ measures taken at Preschool and Grade 1 significantly differed in the amount of variance they could account for in the Grade 1 reading measures, after the variance due to the control measures and speech/language problems had been accounted for.

In the prediction of Grade 1 LetterWord Id, the Preschool TOJ measures accounted for 14.00% of the variance at Step 3 compared to 10.50% with the Grade 1 TOJ measures. This difference in variance accounted for was not significant, $\bar{z}^* = 0.51$, $p > 0.05$. In the prediction of Grade 1 reading rate, the Preschool TOJ measures accounted for 8.00% of the variance at Step 3, compared with 9.10% accounted for by the Grade 1 measures. This difference was also not significant, $\bar{z}^* = -0.15$, $p > 0.05$.

However, there were differences between the two sets of regression analyses in terms of which predictors accounted for significant independent variance in the reading measures. Regardless of when it was measured, ATOJ performance accounted for significant independent components of variance in both reading measures. When measured at Preschool, VTOJ performance did not account for significant independent variance in either reading measure. However, when measured at Grade 1, the standardized regression coefficients (β; see Table 3c) showed that VTOJ performance was a more important predictor than ATOJ performance of variance in LetterWord Id. There was also a trend toward Grade 1 VTOJ performance independently accounting for variance in reading rate.

Reliability of TOJ Measures Across Time

In order to obtain the test–retest reliability, or normative stability, of the TOJ measures across this 6–8 month critical developmental phase, participant's scores on the Auditory and Visual TOJ tasks were ranked and bivariate Spearman correlations between the Preschool and Grade 1 ranks on each measure were calculated. There were significant moderate correlations between the ranks for Preschool and Grade 1 Auditory TOJ, $rs(124) = 0.51$, $p < 0.0001$, and between the ranks for Preschool and Grade 1 Visual TOJ, $rs(125) = 0.54$, $p < 0.0001$. (Pearson correlations between the raw scores at these two times were identical to the Spearman correlations.)

To further assess the extent to which children's location within the distribution was consistent across time, quartiles were formed for each measure at each time and participants' quartile membership from Preschool to Grade 1 was compared. Table 4 presents the percentages of participants in each quartile at Preschool who fell into a particular quartile in Grade 1 on each measure. For both TOJ measures, the consistency was greatest in the lowest and highest quartiles, with more movement across quartiles in the middle of the distribution. On both measures, around half of the participants who were in the lowest quartile at Preschool, remained in the lowest quartile at Grade 1.

DISCUSSION

The current study showed that auditory and visual temporal processing measures obtained at Preschool accounted for significant variance in single letter and word reading accuracy and reading rate (fluency) measured in early Grade 1, even after the effects of age, environment, memory, attentional vigilance, nonverbal ability, and speech/language problems were controlled. The percentage of variance accounted for in the reading measures did not significantly differ

Table 4. Percentage of participants within each quartile on auditory and visual TOJ tasks in Preschool and Grade 1

	Quartile at Grade 1			
Quartile at Preschool	I (%)	II (%)	III (%)	IV (%)
Auditory TOJ task				
I	**44.0**	40.0	8.0	8.0
II	25.0	**40.6**	15.6	18.8
III	10.3	27.6	**41.4**	20.7
IV	5.1	17.9	25.6	**51.3**
Visual TOJ task				
I	**54.5**	18.2	18.2	9.1
II	28.6	**35.7**	25.0	10.7
III	10.3	24.1	**48.3**	17.2
IV	5.7	11.4	31.4	**51.4**

Entries in bold are the percentages whose quartile membership was the same at Preschool and Grade 1 (Cell entries represent percentage of participants within a given quartile at preschool who fell into each quartile at Grade 1).

depending on whether temporal processing was measured at either Preschool or at Grade 1. However, there were some developmental changes in the relationship of the individual temporal processing measures to reading. Reliability of and consistency of performance on the temporal processing measures was moderate.

These results showed that the covariation between temporal processing and reading skills found in older children and adolescents (Cornelissen *et al.*, 1998; Marshall *et al.*, 2001; Olson & Datta, 2002; Talcott *et al.*, 2000, 2002) was present right from the emergence of reading. The normal distributions of these variables in the sample and the significant linear relationships found between temporal processing ability and reading ability support the idea that these are continuously distributed variables that covary in the normal population. In fact, differences in temporal processing abilities that covary with differences in reading ability were present before the emergence of reading. This is consistent with the hypothesis that neurological impairments that underlie the temporal processing deficits are present from a very early point in development, probably occurring *in utero* (Galaburda *et al.*, 1985; Stein, 2001a).

These findings support and extend the longitudinal findings of Lovegrove *et al.* (1986) in the visual domain. There was little overlap between the auditory and visual TOJ measures in the variance accounted for in the reading measures, despite the fact that there were significant moderate correlations between the TOJ measures. This showed that visual and auditory temporal processing were related to different components of early reading. Auditory temporal processing is predicted to be important in early speech perception and the formation of phonemic representations. This is important for the development of phonological processing and, subsequently, for reading development (Benasich & Tallal, 2002; Tallal, 1980). Visual temporal processing is predicted to be important in letter position encoding, global word form perception, binocular stability, and effective saccadic eye movements. Efficiency in these processes is important for effective reading (Habib, 2000; Stein & Talcott, 1999). These specific predictions need testing with a longitudinal design.

The current longitudinal prospective design had advantages over previous studies that used older samples and cross-sectional designs. It controlled for the autoregressive effects of previous reading ability because children were initially pre-readers. Rack, Hulme, and Snowling (1993) argued that this is essential if causal links to reading are to be established. It also provided a measure of the covariation between these perceptual abilities and reading, before any effects of reading failure or reading remediation had occurred. Successful remediation may obscure the expected relationships between reading and temporal processing in older dyslexic readers because reading scores are elevated to normal levels (e.g. see Ahissar *et al.*, 2000). Reading itself may influence temporal processing. A reciprocal relationship was found between phonological processing and reading, such that phonological skills fostered reading development, but learning to read fostered further improvement in phonological skills (Wagner & Torgeson, 1987). If a similar relationship exists between temporal processing and reading, the temporal processing deficits found in older dyslexic readers could be a result of, rather than a cause of, the reading failure (Ramus, 2004). In the current study, participants were pre-readers when the TOJ measures were first obtained, thus, reading or reading failure cannot explain the covariation found between temporal processing ability and subsequent reading ability.

The variance in reading accounted for by the temporal processing measures cannot be explained by a range of factors that were controlled for in the hierarchical regression analyses. Attentional vigilance accounted for independent variance in both reading measures. Previous studies concluded that the poorer performance on temporal processing tasks found in dyslexia was due to impaired attentional vigilance rather than to an underlying perceptual or neurological deficit (Davis *et al.*, 2001; Stuart *et al.*, 2001). The data presented here demonstrated that there was still a significant relationship between temporal processing and reading after the variance due to attentional vigilance was accounted for. It is important that future studies control for the effects of attentional vigilance, however, it cannot explain the relationship between temporal processing and reading in a normative sample.

Previous research found that the relationship between auditory TOJ performance and reading was mediated by the presence of language impairments (Heath *et al.*, 1999; Stark *et al.*, 1988; Tallal & Stark, 1982). Inclusion of the speech/language problem variable in the regression analyses showed that it accounted for a small but significant percentage of variance in reading fluency (reading rate) but could not account for a significant component of variance in letter and word identification (after the variance due to the control factors were accounted for). Importantly, the temporal measures still explained a significant amount of variance in both reading measures, after the variance due to speech/language problems was accounted for. This study used parental report of speech/language problems, which is a very coarse, subjective indicator. For some participants who were receiving speech therapy, there was objective supporting evidence of a problem. Other studies have used objective criteria for SLD, which could explain the differing results. However, the focus of the current study was on a normative sample not on selected groups. In this design, the presence of speech/language problems cannot explain the relationship between temporal processing and reading.

The overall percentage of variance accounted for in reading did not differ depending on whether TOJ performance was measured before or after the emergence of reading. This showed that the predictive relationship was consistent and not simply an artefact of methodological concerns associated with measuring Preschool-aged children, e.g. increased error in the data due to immaturity or greater inattentiveness. There were developmental changes in the specific TOJ measures that predicted unique variance in reading. Performance on the Auditory TOJ task at both Preschool and Grade 1 uniquely accounted for variance in Grade 1 reading. Only when the visual TOJ performance was measured after reading instruction had commenced, did it account for unique variance in reading rate when it. This showed that while temporal processing deficits may be present prior to reading, the increased role that visual temporal processing plays once reading development begins may magnify this effect in the visual system. As reading develops, particularly to the orthographic or fluent stage (Frith, 1985), the role of visual temporal processing increases in importance.

There was moderate test–retest reliability of TOJ measurement over the 6–8 month interval. The current study represented the first reported test–retest reliability for a visual temporal processing measure. For the auditory TOJ measure, the obtained test–retest reliability compared well with that previously reported for this task using a much smaller sample over only a 1-week interval (0.64, Nicolson & Fawcett, 1996). Using a larger ($N = 85$) and an older sample (7–11 years), Waber *et al*. (2001) reported a test–retest correlation of 0.85 over a 1–2 week interval for their auditory TOJ. With Preschool-aged children, test–retest reliability over a longer interval would be confounded with normal development in temporal processing.

There was only moderate consistency in the children's relative positions in the distributions from Preschool to Grade 1. There was individual variation in development in these skills. Around half of the children in the lowest quartile at Preschool, the 'poor temporal processors', remained in the lowest quartile at Grade 1. However, the other half experienced what must amount to greater than average development in these skills and moved into a higher quartile by Grade 1. For other children, development may have been slower than average and those children effectively went backwards in the distribution, i.e. they fell into a lower quartile at Grade 1 than at Preschool. This laboratory is currently investigating the relationship between the growth rate in children's temporal processing skills and reading development. Children who are initially poor temporal processors but who catch up in the early grades of primary school may not experience any long-term reading difficulties. Children who remain poor temporal processors may be those who are at higher risk for long-term reading difficulties.

The temporal processing measures were specifically chosen because they had previously been used with Preschool-aged children. Only two sequential stimuli were presented. Tasks that increase the perceptual load by presenting longer sequences of stimuli may produce stronger relationships to reading. Talcott *et al.* (2002) argued that measures of dynamic changes in sensory stimuli, such as visual motion coherence and auditory frequency modulation detection tasks, produce more consistent relationships with reading than do tasks such as the TOJ tasks. Motion coherence tasks for young children are still in development (Stein, 2003). Evidence of a similar relationship between pre-existing temporal processing ability, measured on a range of tasks, and subsequent reading development, would strengthen support for a causal link.

This study provided the first evidence that impaired temporal processing predates the development of reading difficulty. This strengthens the causal evidence for the temporal processing deficit hypothesis of dyslexia. The results also demonstrated that auditory and visual temporal processing made independent contributions to the variance in reading. Further investigation is required into the specific components in reading that each form of temporal processing predicts. The relationship could not be explained by attentional vigilance, the effects of prior reading experience, speech/language problems, or a range of other factors. Temporal processing measures, which were suitable for Preschool-aged children, would provide useful additional indicators of early risk for reading difficulties, allowing reading intervention programs to be targeted as early as possible. To date, early prediction has been restricted to using measures of phonological processing and letter knowledge. However, longer-term data is required to determine if this predictive relationship between Preschool temporal processing ability and reading is sustained beyond the earliest stage in reading development. Of particular interest would be whether the relative importance of visual temporal processing strengthens as children move into the orthographic stage of reading development and develop automaticity.

ACKNOWLEDGEMENTS

Grants from the School of Applied Psychology, Griffith University and the Learning Disabilities Action Network, Queensland, supported this research. We would like to thank the children, parents, and staff of Ashmore, Arundel, and Southport State Schools for their participation in this project. We would also like to thank Arthur Simpson for writing the program for the visual temporal order judgement task and Emma Howard for assistance with data collection. We are grateful for the comments of anonymous reviewers on an earlier draft of this paper.

References

Ahissar, M., Protopapas, A., Reid, M., & Merzenich, M. M. (2000). Auditory processing parallels reading abilities in adults. *Proceedings of the National Academy of Science, 12*, 6832–6837.

Angus and Robertson's Bookworld (1999). One hundred all-time favourite children's books. Retrieved November 25, 1999 from http://www.bookworld.com.au/kidstop1002.htm.

Benasich, A. A., & Tallal, P. (2002). Infant discrimination of rapid auditory cues predicts later language impairment. *Behavioural Brain Research, 136*, 31–49.

Brannan, J. R., & Williams, M. C. (1988). Developmental versus sensory processing deficit effects on perceptual processing in the reading disabled. *Perception and Psychophysics*, *44*(5), 437–444.

Breier, J. L., Gray, L. C., Fletcher, J. M., Foorman, B., & Klaas, P. (2002). Perception of speech and nonspeech stimuli by children with and without reading disability and attention deficit hyperactivity disorder. *Journal of Experimental Child Psychology, 82*, 226–250.

Bretherton, L., & Holmes, V. M. (2003). The relationship between auditory temporal processing, phonemic awareness, and reading disability. *Journal of Experimental Child Psychology, 84*, 218–243.

Cestnick, L. (2001). Cross-modality temporal processing deficits in developmental phonological dyslexics. *Brain and Cognition, 46*(3), 319–325.

Cestnick, L., & Jerger, J. (2000). Auditory temporal processing and lexical/nonlexical reading in developmental dyslexics. *Journal of the American Academy of Audiology, 11*, 501–517.

Cipielewski, J., & Stanovich, K. E. (1992). Predicting growth in reading ability from children's exposure to print. *Journal of Experimental Child Psychology, 54*, 74–89.

Cornelissen, P. L., Hansen, P. C., Hutton, J. L., Evangelinou, V., & Stein, J. F. (1998). Magnocellular visual function and children's single word reading. *Vision Research*, *38*, 471–482.

Cornelissen, P., Richardson, A., Mason, A., Fowler, S., & Stein, J. (1995). Contrast sensitivity and coherent motion detection measured at photopic luminance levels in dyslexics and controls. *Vision Research*, *35*(10), 1483–1494.

Cunningham, A. E., & Stanovich, K. E. (1993). Children's literacy environments and early word recognition subskills. *Reading & Writing, 5*(2), 193–204.

Davis, C., Castles, A., McAnally, K., & Gray, J. (2001). Lapses of concentration and dyslexic performance on the Ternus task. *Cognition*, *81*, B21–B31.

de Martino, S., Espesser, R., Rey, V., & Habib, M. (2001). The 'Temporal Processing Deficit' hypothesis in dyslexia: New experimental evidence. *Brain and Cognition, 46*, 104–108.

Dolch, E. W. (1936). A basic sight vocabulary. *Elementary School Journal, 36*, 456–460.

Eden, G., van Meter, J., Rumsey, J., Maisog, J., Woods, R., & Zeffiro, T. (1996). Abnormal processing of visual motion in dyslexia revealed by functional brain imaging. *Nature*, *382*, 66–69.

Facoetti, A., & Molteni, M. (2001). The gradient of visual attention in developmental dyslexia. *Neuropsychologia, 39*(4), 352–357.

Farmer, M. E., & Klein, R. M. (1993). Auditory and visual temporal processing in dyslexic and normal readers. In P. Tallal, A. M. Galaburda, R. R. Llinas, & C. von Euler (Eds.), Annals of the New York Academy of Sciences, Vol. 682: *Temporal information processing in the nervous system—Special reference to dyslexia and dysphasia* (pp. 339–341). New York: New York Academy of Sciences.

Farmer, M. E., & Klein, R. M. (1995). The evidence for a temporal processing deficit linked to dyslexia: A review. *Psychonomic Bulletin*, *2*(4), 460–493.

Fawcett, A. J., & Nicolson, R. I. (1995). The dyslexia early screening test. *Irish Journal of Psychology*, *16*(3), 248–259.

Fletcher, J. M., Foorman, B. R., Boudousquie, A., Barnes, M. A., Schatschneider, C., & Francis, D. J. (2002). Assessment of reading and learning disabilities: A research-based intervention-oriented approach. *Journal of School Psychology, 40*(1), 27–63.

Frith, U. (1985). Beneath the surface of developmental dyslexia. In K. E. Patterson, J. C. Marshall, & M. Coltheart (Eds.), *Surface dyslexia*. London: Routledge and Kegan Paul.

Galaburda, A. M., Menard, M. T., & Rosen, G. D. (1994). Evidence for aberrant auditory anatomy in developmental dyslexia. *Proceedings of the National Academy of Science*, *91*, 8010–8013.

Galaburda, A. M., Sherman, G. F., Rosen, G. D., Aboitiz, F., & Geschwind, N. (1985). Developmental dyslexia: Four consecutive patients with cortical anomalies. *Annals of Neurology*, *18*(2), 222–233.

Glutting, J. J., & Oakland, T. (1993). *Guide to the assessment of test-session behaviour for WISC-III and WIAT*. San Antonio: Psychological Corporation.

Habib, M. (2000). The neurological basis of developmental dyslexia: An overview and working hypothesis. *Brain*, *123*, 2373–2399.

Hari, R., & Renvall, H. (2001). Impaired processing of rapid stimulus sequences in dyslexia. *Trends in Cognitive Neuroscience*, *5*(12), 525–532.

Heath, S. M., Hogben, J. H., & Clark, C. D. (1999). Auditory temporal processing in disabled readers with and without oral language delay. *Journal of Child Psychology and Psychiatry*, *40*(4), 637–647.

Livingstone, M., Rosen, G., Drislane, F., & Galaburda, A. M. (1991). Physiological and anatomical evidence for a magnocellular deficit in developmental dyslexia. *Proceedings of the National Academy of Science*, *88*, 7943–7947.

Lovegrove, W., Slaghuis, W., Bowling, A., Nelson, P., & Geeves, E. (1986). Spatial frequency processing and the prediction of reading ability: A preliminary investigation. *Perception and Psychophysics*, *40*(6), 440–444.

McBride-Chang, C., Manis, F. R., Seidenberg, M. S., Custodio, R. G., & Doi, L. M. (1993). Print exposure as a predictor of word reading and reading comprehension in disabled and nondisabled readers. *Journal of Educational Psychology*, *85*(2), 230–238.

Marshall, C. M., Snowling, M. J., & Bailey, P. J. (2001). Rapid auditory processing and phonological ability in normal readers and readers with dyslexia. *Journal of Speech, Language, and Hearing*, *44*(4), 925–940.

Nicolson, R. I., & Fawcett, A. J. (1996). *The dyslexia early screening test*. London: The Psychological Corporation.

Nittrouer, S. (1999). Do temporal processing deficits cause phonological processing problems? *Journal of Speech, Language, and Hearing Research*, *42*, 925–942.

Olson, R., & Datta, H. (2002). Visual-temporal processing in reading-disabled and normal twins. *Reading and Writing: An Interdisciplinary Journal, 15*, 127–149.

Rack, J. P., Hulme, C., & Snowling, M. J. (1993). Learning to read: A theoretical synthesis. In H. W. Reese (Ed.), *Advances in child development and behaviour,* Vol. 24 (pp. 99–132). San Diego: Academic Press.

Ramus, F. (2004). Should neuroconstructivism guide developmental research? *Trends in Cognitive Sciences*, *8*(3), 100–101.

Raven, J. C., Court, J. H., & Raven, J. (1986). *Raven's coloured matrices.* London: H.K. Lewis.

Reed, M. A. (1989). Speech perception and the discrimination of brief auditory cues in reading disabled children. *Journal of Experimental Child Psychology, 48*, 270–292.

Rey, V., de Martino, S., Espesser, R., & Habib, M. (2002). Temporal processing and phonological impairment in dyslexia: Effect of phoneme lengthening on order judgement of two consonants. *Brain and Language*, *80*, 576–591.

Senechal, M., LeFevre, J., Thomas, E., & Daley, K. E. (1998). Differential effects of home literacy experiences on the development of oral and written language. *Reading Research Quarterly*, *33*(1), 96–116.

Share, D. L., Jorm, A. F., Maclean, R., & Matthews, R. (2002). Temporal processing and reading disability. *Reading & Writing, 15*(1–2), 151–178.

Shaywitz, S. E., Escobar, M. D., Shaywitz, B. A., Fletcher, J. M., & Makuch, R. (1992). Evidence that dyslexia may represent the lower tail of a normal distribution of reading ability. *New England Journal of Medicine*, *326*(3), 145–150.

Shaywitz, S. E., Shaywitz, B. A., Fletcher, J. M., & Escobar, M. D. (1990). Prevalence of reading disability in boys and girls: Results of the Connecticut longitudinal study. *Journal of the American Medical Association, 254*, 998–1002.

Stark, R. E., Tallal, P., & McCauley, R. J. (Eds.). (1988). *Language, speech, and reading disorders in children*: *Neuropsychological studies*. Boston: College-Hill Press.

Steiger, J. H. (1980). Test for comparing elements of a correlation matrix. *Psychological Bulletin*, *87*, 245–251.

Stein, J. (2001a). The magnocellular theory of developmental dyslexia. *Dyslexia*, *7*, 12–36.

Stein, J. (2001b). The sensory basis of reading problems. *Developmental Neuropsychology, 20*(2), 509–534.

Stein, J. (2003). Visual motion sensitivity and reading. *Neuropsychologia, 41*, 1785–1793.

Stein, J., & Talcott, J. (1999). Impaired neuronal timing in developmental dyslexia: The magnocellular hypothesis. *Dyslexia, 5*, 59–77.

Stuart, G. W., McAnally, K. I., & Castles, A. (2001). Can contrast sensitivity functions in dyslexia be explained by inattention rather than a magnocellular deficit? *Vision Research, 41*, 3205–3211.

Talcott, J. B., Witton, C., Hebb, G. S., Stoodley, C. J., Westwood, E. A., France, S. J., & Hansen, P. C. (2002). On the relationship between dynamic visual and auditory processing and literacy skills: Results from a large primary-school study. *Dyslexia*, *8*, 204–225.

Talcott, J. B., Witton, C., McLean, M. F., Hansen, P. C., Rees, A., Green, G. G. R., & Stein, J. F. (2000). Dynamic sensory sensitivity and children's word decoding skills. *Proceedings of the National Academy of Sciences, 97*, 2952–2957.

Tallal, P. (1980). Auditory temporal perception, phonics, and reading disabilities in children. *Brain and Language*, *9*, 182–198.

Tallal, P., & Stark, R. E. (1982). Perceptual/motor profiles of reading impaired children with or without concomitant oral language deficits. *Annals of Dyslexia, 32*, 163–176.

Vellutino, F. R. (1979). *Dyslexia*: *Theory and research*. London: MIT Press.

Waber, D. P., Weiler, M. D., Wolff, P. H., Bellinger, D., Marcus, D. J., Ariel, R., Forbes, P., & Wypij, D. (2001). Processing of rapid auditory stimuli in school-aged children referred for evaluation of learning disorders. *Child Development*, *72*(1), 37–49.

Wagner, R. K., & Torgesen, J. K. (1987). The nature of phonological processing and its causal role in the acquisition of reading skills. *Psychological Bulletin*, *101*, 192–212.

Woodcock, R. W. (1997). *Woodcock diagnostic reading battery.* Itasca, Illinois: Riverside Publishing.

Wright, B. A., Bowen, R. W., & Zecker, S. G. (2000). Nonlinguistic perceptual deficits associated with reading and language disorders. *Current Opinion in Neurobiology*, *10*(4), 482–486.

