

This article was downloaded by: [Griffith University Library]

On: 13 May 2009

Access details: Access Details: [subscription number 773444546]

Publisher Psychology Press

Informa Ltd Registered in England and Wales Registered Number: 1072954 Registered office: Mortimer House, 37-41 Mortimer Street, London W1T 3JH, UK



## Developmental Neuropsychology

Publication details, including instructions for authors and subscription information:

<http://www.informaworld.com/smpp/title-content=t775653638>

### Auditory and Visual Processing in Children With Dyslexia

Craig M. Wright<sup>ab</sup>; Elizabeth G. Conlon<sup>a</sup>

<sup>a</sup> School of Psychology, Gold Coast Campus, Griffith University, Queensland, Australia <sup>b</sup> Understanding Minds, Gold Coast, Australia

Online Publication Date: 01 May 2009

**To cite this Article** Wright, Craig M. and Conlon, Elizabeth G. (2009) 'Auditory and Visual Processing in Children With Dyslexia', *Developmental Neuropsychology*, 34:3, 330 — 355

**To link to this Article:** DOI: 10.1080/87565640902801882

**URL:** <http://dx.doi.org/10.1080/87565640902801882>

PLEASE SCROLL DOWN FOR ARTICLE

Full terms and conditions of use: <http://www.informaworld.com/terms-and-conditions-of-access.pdf>

This article may be used for research, teaching and private study purposes. Any substantial or systematic reproduction, re-distribution, re-selling, loan or sub-licensing, systematic supply or distribution in any form to anyone is expressly forbidden.

The publisher does not give any warranty express or implied or make any representation that the contents will be complete or accurate or up to date. The accuracy of any instructions, formulae and drug doses should be independently verified with primary sources. The publisher shall not be liable for any loss, actions, claims, proceedings, demand or costs or damages whatsoever or howsoever caused arising directly or indirectly in connection with or arising out of the use of this material.

## Auditory and Visual Processing in Children With Dyslexia

Craig M. Wright

*School of Psychology, Gold Coast Campus  
Griffith University, Queensland, Australia  
Understanding Minds, Gold Coast, Australia*

Elizabeth G. Conlon

*School of Psychology, Gold Coast Campus  
Griffith University, Queensland, Australia*

This study investigated the temporal stability and longitudinal replicability of visual and auditory sensory processes found to be poor in children with dyslexia. Seventy children with dyslexia and 52 normal readers were tested twice, 9 months apart, on measures of visual and auditory sensory processing and on phonological and orthographic skills. About 30% of children with dyslexia were found to have sensory deficits. Associations were found between sensory and cognitive skills. Based on analyses of agreement, the temporal stability of the sensory tasks was poor. Future research should develop sensory measures with high temporal stability that can control for maturation.

Developmental dyslexia occurs in 5%–10% of the population (Yule, Rutter, Berger, & Thompson, 1973). Most children with dyslexia have a phonological processing deficit (Snowling, 2000; Ramus, 2004). This impairment is thought to adversely affect the child's word recognition system by interfering with the ability to establish links between spoken sounds and written letters (Byrne & Fielding-Barnsley, 1989). Although the existence of phonological and word recognition difficulties in dyslexia is well established (see Vellutino et al., 1996 for a review), the evidence for sensory processing deficits in the visual and auditory domains hypothesized to underlie these cognitive difficulties is not.

### AUDITORY PROCESSING IN DYSLEXIA

The auditory processing theory (Tallal, 1980; Witton, Stein, Stoodley, Rosner, & Talcott, 2002) argues that the phonological deficit that is usually involved in dyslexia is attributable to a low-level auditory perceptual deficit (Pasquini, Corriveau, & Goswami, 2007; Witton et al., 2002). Difficulties in the detection of dynamic changes in auditory stimuli is one form of auditory processing that may ac-

count for difficulties in phonological analysis in individuals with dyslexia (Goswami et al., 2002; Richardson, Thomson, Scott, & Goswami 2004; Witton et al., 2002). In the research on dynamic (sometimes referred to as “temporal”) auditory perception of this type sensitivity has been investigated using frequency modulation (FM) detection tasks. In an FM detection task, discrimination between a pure tone stimulus and a frequency-modulated stimulus is used to determine sensitivity to dynamic changes in auditory stimuli. The physiological mechanisms used for FM detection vary according to the nature of the modulation (Moore & Sek, 1995). When the carrier tone is of low frequency and the rate of modulation low (around 2 Hz), detection depends on temporal information. Auditory neurons fire in response to the frequency (phase-locking) and detection is performed by tracking changes in phase-locking information over time (Halliday & Bishop, 2006). The upper frequency limit for phase-locking is approximately 4–5 Hz in mammals (Palmer & Russell, 1986). Beyond this, detection of more rapidly modulating tones is thought to be based on the place of excitation on the basilar membrane; a separate process to that used for detection of slower frequencies (Moore & Sek, 1995). In FM detection tasks, the ability to detect small differences between the frequency modulated tone and the pure tone represents greater auditory processing sensitivity.

Support for the auditory processing hypothesis has been obtained from studies that have found reduced sensitivity in groups with dyslexia to low (2 Hz) rates of FM (Huslander et al., 2004; Ramus et al., 2003; Talcott et al., 2003), but not high rates of FM (240 Hz; Witton et al., 1998; Witton et al., 2002). Temporal aspects of the speech signal are important for carrying the phonological information necessary for speech perception and speech intelligibility (Drullman, Festen, & Plomp, 1994; Hirsch, 1959; Shamma, 2003; Shannon, Zeng, Kamath, Wygonski, & Ekelid, 1995). It has therefore been proposed that the apparent lack of sensitivity to auditory stimuli such as 2 Hz FM, which require temporal resolution based on phase-locking cues, may indirectly cause reading problems in individuals with dyslexia by impairing speech perception (Edwards et al., 2004; Pasquini et al., 2007; Witton et al., 1998; Witton et al., 2002).

In support of the aforementioned hypothesis, associations have been reported between temporal auditory processing of FM, phonological processing skills, and reading ability (Talcott et al., 1999; Talcott, Witton, et al., 2000; Witton et al., 2002; Witton et al., 1998). However, there have been failures to replicate FM detection deficits (Boets, Wouters, van Wieringen, & Ghesquiere, 2006; Halliday & Bishop, 2006; Hill, Bailey, Griffiths, & Snowling, 1999) and there is evidence that deficits in processing frequency modulations in dyslexia groups may not be confined to temporal stimuli (Hari, Saaskilahti, Helenius, & Uutela, 1999). There is also growing evidence that only a sub-group of individuals with dyslexia have these types of auditory sensory deficits (Boets et al., 2006; Edwards et al., 2004; Ramus et al., 2003; Richardson et al., 2004; Witton et al., 1998; White, Frith et al., 2006; Witton et al., 2002; Rosen, 2003).

## VISUAL TEMPORAL PROCESSING IN DYSLEXIA

The visual magnocellular deficit hypothesis (Lovegrove, 1993; Stein & Walsh, 1997) posits that visual sensory deficits can interfere with the processing of written letters and hence lead to word-level reading difficulties (Cornelissen, Hansen, Gilchrist et al., 1998; Talcott, Witton et al., 2000). This hypothesis is based on the physiological response of neurons in the magnocellular system which are most sensitive to rapid transitions such as movement, and stimuli of low spatial and high temporal frequencies (Merigan, Katz, & Maunsell, 1991). Supporting evidence for the

magnocellular deficit hypothesis has been obtained from studies investigating anatomical structures (Galaburda & Livingstone, 1993), visual evoked potentials (Kubova, Kuba, Peregrin, & Novakova, 1996; Lehmkuhle, Garzia, Turner, Hash, & Baro, 1993; Livingstone, Rosen, Drislane, & Galaburda, 1991; May, Lovegrove, Martin, & Nelson, 1991), and behavioral measures of visual function (Felmingham & Jacobson, 1995; Martin & Lovegrove, 1987; Slaghuis & Ryan, 1999, 2006). These studies have shown that groups with dyslexia are significantly less sensitive than control groups on tasks that measure magnocellular visual function. Groups with dyslexia do not have reduced sensitivity on measures that are processed in the parvocellular visual pathway, a system most sensitive to high spatial *and* low temporal frequencies (Lovegrove, Martin, & Slaghuis, 1986; Hansen, Stein, Orde, Winter, & Talcott, 2001).

These findings have been extended to the middle temporal area (MT) in the dorsal pathway. The predominant neuronal input to this area is from neurons in the magnocellular pathway (Merigan & Maunsell et al., 1993; Schiller, Logothetis, & Charles, 1990), although some input from parvocellular cells cannot be discounted. This area processes motion signals, such as speed and direction of motion. Research using functional magnetic resonance imaging (fMRI) (Demb, Boynton, & Heeger, 1998; Eden et al., 1996) has found reduced neural activity in this visual area for groups with dyslexia. In addition, using behavioral techniques reduced motion sensitivity has been found in dyslexia when compared to control groups (Conlon, Sanders, & Zapart, 2004; Cornelissen, Richardson, Mason, Fowler, & Stein, 1995; Demb, Boynton, Best, & Heeger, 1998; Hansen et al., 2001; Raymond & Sorenson, 1998; Slaghuis & Ryan, 1999; Talcott et al., 2003; Talcott, Hansen, Assoku, & Stein, 2000; Wilmer, Richardson, Chen, & Stein, 2004).

A measure that engages the magnocellular and dorsal pathways is the global motion coherence task. This task uses random dot kinematograms (RDK) to measure sensitivity to dynamic changes in motion. A proportion of the dots referred to as signal dots appear to move in a specific direction, with the remaining noise dots containing no specific directional signal (see Figure 1). Displacing

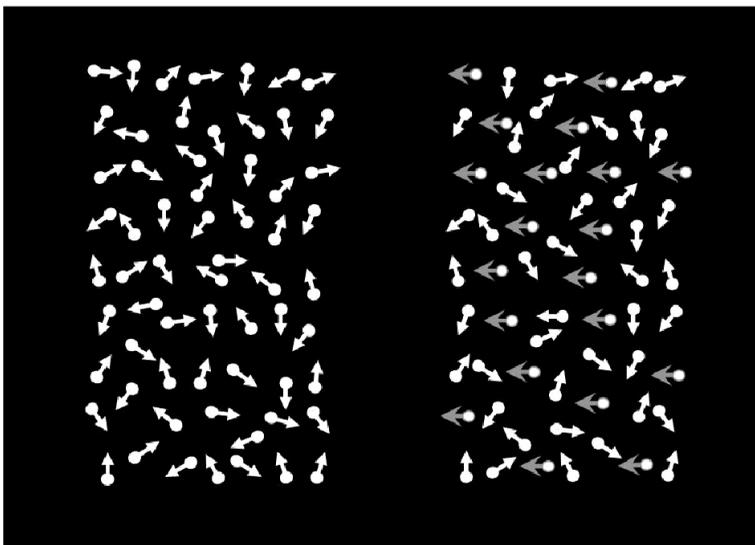


Figure 1 Representation of the stimulus used in the global motion coherence task.

the signal elements incrementally by the same distance and the same direction across a number of successively presented frames generates directional movement. Noise elements change direction between each frame, producing random noise. The percentage of signal dots required when determining the direction of motion is the measure of sensitivity used in this study. This measure of sensitivity relies both on the quality of the lower level signals from the magnocellular pathway and from the efficiency of the directional motion processing mechanisms at MT when summing the individual motion signals (Newsome & Parre, 1988).

Reduced sensitivity to global motion has been associated with phonological processing and orthographic coding (Conlon et al., 2004; Cornelissen, Hansen, Hutton, Evangelinou, & Stein, 1998; Cornelissen, Hansen, Gilchrist et al., 1998; Talcott, Witton et al., 2000; Talcott et al., 2002; Talcott et al., 1998; Witton et al., 1998). These findings provide some support for the theory that poor quality visual sensory representations may contribute to specific difficulties in forming the orthographic and phonological codes critical for skilled reading. However, there have been failures to replicate findings of visual sensory deficits in groups with dyslexia (Edwards et al., 2004; Hayduk, Bruck, & Cavanagh, 1996; Kronbichler, Hutzler, & Wimmer, 2002; Williams, Stuart, Castles, & McAnally, 2003). Several studies have also reported that only a subgroup of individuals with dyslexia have a visual sensory deficit (Edwards et al., 2004; Pellicano & Gibson, 2008; Ramus et al., 2003; White, Milne et al., 2006). Additionally, some studies have found similar visual deficits in groups of children with other developmental disorders such as autism (White, Frith, et al., 2006), suggesting that a magnocellular deficit may not be specific to dyslexia.

### HETEROGENEITY IN FINDINGS OF SENSORY DEFICITS IN DYSLEXIA

The inconsistent results obtained in the literature reviewed thus far may be explained by the heterogeneous behavioral characteristics found in individuals with dyslexia (Slaghuis & Ryan, 2006; Stein, 2001). Slaghuis (2007) has argued that many studies that have failed to obtain evidence of sensory deficits in dyslexia groups have used classification criteria that fail to either clearly define dyslexia or use criteria that fail to select children with specific phonological deficits. For example, one study that failed to obtain evidence of visual deficits in children with dyslexia classified dyslexia on the basis of poor reading fluency and poor spelling (Kronbichler et al., 2001). In that study the dyslexia and control groups did not differ in sensitivity on a global motion task found in other studies to show evidence of reduced sensitivity in groups with dyslexia (e.g., Hansen et al., 2001; Solan, Shelley-Tremblay, Hansen, & Larson, 2004, 2007; Talcott et al., 2003)

The temporal stability of the sensory processing measures may also contribute. Correlations of between .70 and .75 have been reported between threshold estimates within testing sessions on measures of global motion processing (Conlon et al., 2004; Cornelissen et al., 1995; Talcott et al., 1999). In one longitudinal study that assessed global motion sensitivity in a group of children with dyslexia on two occasions, 12 months apart, all of the children with dyslexia and a global motion deficit at the first testing session also had a global motion deficit at the second testing session. One further child with dyslexia had a global motion deficit at retest, but not in the initial testing phase. None of the control group had a global motion deficit at either testing phase (Raymond & Sorenson, 1998). Increased sensitivity to global motion was also found for all children at retest. In addition, the temporal stability found on a measure of frequency discrimination assessed twice 18

months apart in children with specific language impairments was .64 (Bishop & McArthur, 2005). In children, the differences in stability found on measures of auditory and visual sensory processing has been explained by poor vigilance (Stuart, McAnally & Castles, 2001) or from the effects of maturation (Braddick, Atkinson, & Wattam-Bell, 2003; Bishop & McArthur, 2005).

## THE CURRENT STUDY

In the current study, sensory sensitivity was assessed in children with or without dyslexia at two Phases, separated by a 9-month interval. Three measures of dynamic auditory and visual processing were used. The auditory tasks were the 2 and 240 Hz FM detection tasks found previously to provide evidence that adults with dyslexia had reduced sensitivity to the temporal, but not the non-temporal measure of auditory processing (Witton et al., 2002). Sensitivity to global motion was assessed using the global motion task used in previous research (e.g., Hansen et al., 2001; Solan et al., 2007) and that has been shown to separate between dyslexia and control groups. The study aimed to determine if sensory processing deficits in children with dyslexia could be externally replicated using these tasks, in addition to being internally replicated across time. The temporal stability of the measures of sensory processing was assessed. It was expected that the temporal stability would be high if the visual and auditory sensory deficits found previously in groups with dyslexia were replicable. It was also expected that children with a deficit in visual and/or auditory sensory processing at Phase 1 would be the same children with visual and/or auditory sensory deficits at Phase 2. Finally, it was hypothesized that if these deficits were directly associated with reading sub-skills such as phonological processing or orthographic coding skills, then associations between these and the sensory measures would be stable across time.

## METHOD

### Participants

One hundred and thirty participants with English as a first language were recruited from 8 primary schools. There were 75 children with dyslexia ( $M = 8.5$  years;  $SD = 1.4$  years) and 55 children who were normal readers ( $M = 8.5$  years;  $SD = 1.25$  years). Forty-six of children with dyslexia were males, and 34 of the normal readers were male. Children were included in the sample if they had a standardized score of 90 or above on the Colored Progressive Matrices (CPM; Raven et al., 1995), a standardized non-verbal measure of ability. No child had a history of (a) recurrent ear infections, (b) severe hearing problems and uncorrected vision problems, (c) severe emotional problems, (d) diagnosis of attention deficit hyperactivity disorder (ADHD) or (e) diagnosed developmental disorder (e.g., Autism Spectrum Disorder). Evidence of the presence of each of these disorders was obtained from the students' school records.

Reading skills were assessed using the Basic Reading Cluster (BRC) of the Woodcock Diagnostic Reading Battery (WDRB; Woodcock, 1997). The BRC is derived from the participant's scores on the Word Identification and Word Attack subtests. The rationale behind using single word-reading and -decoding measures rather than text reading accuracy was that these measures provided a context-free measure of the word-level skills that are accepted to be the most basic and

ubiquitous (Vellutino et al., 2004). Given that the word-reading deficits in dyslexia are dimensional rather than categorical (Shaywitz, Escobar, Shaywitz, Fletcher, & Makugh, 1992) it was necessary to adopt an arbitrary criterion to define dyslexia. Where to place the cutoff point is a methodological problem for all studies. In the current study, a participant scoring at or below the 15th percentile (more than 1 standard deviation below the population mean) on the BRC was included in the group with dyslexia. Participants included in the control group had to score at or above the 40th percentile on the BRC. The use of these criteria has been suggested by Snowling (2000) who regards word-level skills at or below the 15th percentile on the BRC in otherwise typical children as a good indicator of the anomalous deficits in word-decoding that are the hallmark of dyslexia. These criteria have been adopted in a number of studies (e.g., Vellutino et al., 1996). The normative population against which all participants were compared consisted of 3,245 children of school age in schools in the United States (Woodcock, 1997).

The data from five children with dyslexia and three controls were subsequently removed from the sample because of excessive motor activity and inattention observed during testing. The final sample consisted of 70 children with dyslexia and 52 controls. A description of the sample characteristics is presented in Table 1. The study had approval from the University Human Ethics Committee, which adheres to the guidelines of the National Health and Medical Research Council of Australia. The parents of all selected children provided written permission for their child to participate in the study.

Measures

*Psychometric and Reading Tests*

The Colored Progressive Matrices (CPM; Raven, Court, & Raven, 1995) was used as a measure of non-verbal ability. Word and non-word reading skills were measured using the WDRB (Woodcock, 1997). A measure of oral reading proficiency was obtained using the Neale Analysis of Reading Ability—Third Edition (Neale, 1999).

*Short-Term Verbal Memory*

The digit span task from the Wechsler Intelligence Scale for Children—IV (WISC—IV; Wechsler, 2003) was used as a measure of short-term verbal memory. Total scores for digits forward and digits backward were converted to percentile ranks.

TABLE 1  
Selection Measures Including Means and 95% Confidence Intervals for Dyslexia and Control Groups

	<i>Control (N = 52)</i>		<i>Dyslexia (N = 70)</i>	
Age (years)	8.58	(8.2–8.94)	8.62	(8.27–8.98)
IQ	106.93	(104.4–109.4)	104.54	(102.8–106.3)
WI	63.9	(58.5–69.3)	9.3	(8.3–10.27)
NW	76.6	(70–83)	12	(11.73–12.86)
BRC	70.4	(66.2–74.5)	10.8	(10.2–11.3)

*Note.* IQ = standard score on CPM; WI = Word identification percentile rank; NW = Nonword reading percentile rank; BRC = Basic Reading Cluster percentile rank.

### *Orthographic and Phonological Processing Measures*

**Orthographic coding.** The Word-Pseudohomophone task (Olson, Fosberg, Wise, & Rack, 1994) was used to measure orthographic skill. Stimuli were generated by the V-Scope software package (Enns & Rensink, 1992) on a Power Macintosh with a standard monitor. Two words were presented side by side in 28-point Arial font. One was a high frequency word (e.g., take) and the other was a nonsense word with identical phonological output (e.g., taik). This task is considered a measure of orthographic coding because identification of the correctly spelled word requires the child to have an intact memory for the orthographic form of the word because no phonological cues are available for discrimination. A series of 10 practice trials were conducted prior to presentation of 80 test items that were presented in 4 blocks of 20 trials. Feedback was given after each trial. On each trial participants were instructed to point to the word from each pair that was correctly spelled. Split-half reliability for this task is .93 (Olson et al., 1994).

**Phoneme elision (PE).** The Phoneme Segmentation subtest from the Dyslexia Screening Test (DST; Fawcett & Nicholson, 1996) was used as a measure of phoneme elision ability. The first part of the task requires deletion of syllables (say rainbow without the /bow/), blends (say stake without the /st/), and phonemes (say igloo without the /l/) from orally presented words. The second part of the task required the participant to transpose the initial phoneme in two orally presented words (spoonerisms). For example, Shirley Bassey becomes Birley Shassey. Each correct response received 1 point (maximum score = 15;  $r = .88$  for test-retest).

**Syllable blending, phoneme blending, rhyme oddity awareness, phoneme segmentation.** These abilities were assessed using selected subtests of the Sound Linkage Test of Phonological Awareness (Hatcher, 2000). On the syllable blending subtest participants had to blend orally presented syllables to form a word (win – dow becomes window). The phoneme blending test required participants to blend a string of orally presented phonemes to form a word (d-i-s-c becomes disc). The rhyme oddity test required participants to select the word that did not rhyme from a group of three orally presented words (dog pot log). The phoneme segmentation test required participants to segment orally presented words into their constituent phonemes (cost becomes c-o-s-t). Each correct response received 1 point (maximum = 24;  $r = .94$  for internal consistency). This variable was designated Phonological Awareness (PA).

**Rapid automatized naming (RAN).** The RAN test from the DST (Fawcett & Nicholson, 1996) required participants to produce the name of 20 familiar objects presented as two-dimensional drawings on a card. The test provides the opportunity for the participant to familiarize him- or herself with an untimed practice trial using stimuli identical to the test stimuli. Participants were asked to name the test stimuli as soon as possible following presentation without making mistakes. Performance was taken as the time to correctly name all the test stimuli and was measured with a digital stopwatch ( $r = .85$  for test-retest).

### *Sensory Processing Measures*

**Visual coherent motion.** Thresholds for detecting coherent motion were measured using the double panel task developed by Hansen et al. (2001). Stimuli were displayed on a laptop PC with a 15-inch LCD screen. The frame rate of the monitor was 13.3 msec (screen refresh 75 Hz).

In the motion task two panels, each with 300 high luminance ( $130 \text{ cd/m}^2$ ) white dots (1 pixel) were presented on a low luminance ( $0.98 \text{ cd/m}^2$ ) background. From a viewing distance of 57 cm each of the panels subtended  $10^\circ \times 14^\circ$  of visual angle. These were separated by a dark stripe subtending  $5^\circ$  of visual angle (see Figure 1). One panel contained a variable percentage of signal dots that moved coherently with an angular velocity of 7.0 %/s. During a single trial the direction of motion of the signal dots, left or right was reversed every 572 msec. The second panel contained noise elements only. A single animation frame was 26.6 msec with each signal dot having a lifetime of three animation frames (79.8 msec), after which the signal dots disappeared and were then regenerated at a randomly selected location within the same stimulus panel. Motion coherence threshold percentage was corrected for this finite dot lifetime. Noise dots randomly changed direction in a Brownian manner with each screen refresh. Each trial contained 25 frames with a total stimulus duration of 2.7 sec.

Percentage of coherent motion was corrected for the finite lifetime of the dots. The percentage of target dots within a given software animation frame was varied to each participant's detection threshold from an initial starting value of 75% coherence using a weighted one-up, one-down adaptive staircase technique. This produced threshold estimates at the 75% correct level (Kaernbach, 1991). For correct responses the motion coherence of the target stimulus was decreased by 1 dB (a factor of 1.122). For incorrect responses the proportion of signal dots was increased by 3 dB (a factor of 1.412). The staircase procedure was terminated after 10 reversals and detection threshold was defined as the geometric mean of the final 8 reversals. Catch trials in which coherent motion depth was the same as the starting coherency (75%) were included at random (at least once every five trials) during each block to evaluate participant vigilance. Two blocks of test trials were conducted. The threshold of greatest sensitivity was taken as the participant's motion detection threshold.

Binocular viewing of the RDK patches was conducted in a darkened room where lighting was held constant at  $\sim 5 \text{ cd/m}^2$ . All participants were light adapted prior to presentation at a viewing distance of 57 cm held constant by a chinrest. Participants were instructed to inspect the two stimulus patches and report which patch contained coherent motion ("which had the dots moving side to side"). Feedback was given by means of a high (correct) or low (incorrect) tone after each response. Each participant completed practice trials before testing began. The coherence for the practice trials was fixed at a value well above the average threshold for all participants. Practice testing continued until the criteria of five consecutively correct trials was met.

*Psychoacoustic measures.* Tasks for measuring sinusoidal frequency modulations (FM) of a 1 kHz tone were developed by Witton (2002). The target stimuli were 2 Hz FM and 240 Hz FM and were assessed in separate tasks. The acoustic stimuli were generated using DirectX7 software on a laptop PC. For each trial, two tones of 1,000 msec duration were presented. One was a pure tone and the other was the modulated (target) tone separated by an ISI of 500 msec. The interval containing the target tone was selected at random by the stimulus program. All tones were gated with 20 msec cosine<sup>2</sup> rise and fall times and were presented at approximately 70 dB SPL through AKG K100 closed cell headphones.

Each threshold measurement began with 5 practice trials where the modulation depth (the extent of the sinusoidal deviation of the amplitude or frequency from that of the carrier; Witton, 2002) of the target tone was fixed at a value well above the average threshold for all participants. If an error was made on the practice trials, practice testing was continued until the participant made 5 consecutive correct responses.

For test trials the modulation depth of the target tone was adjusted to each participant's detection threshold using a weighted one-up, one-down adaptive staircase technique. For each correct response the modulation depth was reduced by 1 dB and for each incorrect response the modulation depth was increased by 3 dB (Kaernbach, 1991). The staircase procedure was terminated after 10 reversals and the detection threshold was defined as the geometric mean of the final 8 reversals. Catch trials in which the modulation depth of the target tone was the same as the starting depth for each FM task were included at random intervals during the testing phase to evaluate participant vigilance.

While listening to the acoustic tones participants watched two parrots, one blue and one green, on the computer screen. The effects were generated so that the blue parrot appeared to make the first sound and the green parrot the second sound. After listening to both sounds participants pointed to the bird that made the modulated sound. The experimenter recorded the participant's response by clicking the computer mouse on the bird the participant selected. Participants were informed that when they responded correctly, the bird would lay an egg for them. The goal of the task was to get as many eggs as possible.

### Procedure

The test battery was administered during the first month of the school year (Phase 1). Administration was conducted in a quiet room at the participant's school, free from visual and acoustic distractions. Testing took approximately 2 hours to complete and was typically conducted in two sessions. Phase 2 of the data collection took place 9 months later. Visual and auditory processing measures were repeated, together with the measures of phonological and orthographic processing and oral reading rate. Administration of all measures for Phase 2 took approximately 1.5 hours to complete and was typically conducted in at least two sessions. The order of presentation of each of the measures was counterbalanced across participants and regular breaks were taken between tasks.

### Data Analysis

Independent groups *t*-tests were conducted on the cognitive measures at Phase 1 and Phase 2 of the study. The effect size Cohen's *d*, which describes the strength of the effect provides a measure of the distance between group means and is presented in standard deviation units. An effect size of .8 represents a large effect (Cohen, 1990). Mixed factorial analyses of variance using testing phase and reader groups as independent variables were conducted on each of the sensory processing measures. The temporal stability of the sensory measures was assessed using intraclass correlation coefficients (ICCs) for agreement and consistency. These evaluate the consistency and actual sensitivity or agreement of the measures across time. The 95% confidence intervals of agreement and consistency are also reported (McGraw & Wong, 1996). The agreement between the sensitivity estimates on the auditory and visual tasks from Phase 1 to Phase 2 were further investigated by comparing the differences in sensitivity obtained on each task over time with the overall mean sensitivity scores on each task. This technique provides a graphical representation of repeatability or agreement of measurement over time (Bland & Altman, 1986; 1999). Deviance analysis (Ramus et al., 2003) was used to determine the proportion of children with sensory processing deficits at each phase of testing. Independent groups *t*-tests were used to determine if groups with dyslexia and a sensory deficit differed from groups with dyslexia and no sensory deficit on the cognitive processing measures. Correlation

and regression analyses were used to investigate the associations between orthographic and phonological processes and the measures of sensory processing at each testing phase.

## RESULTS

### Psychometric Tests

At Phase 1 testing the group with dyslexia were significantly less accurate than the control group on measures of Phonological awareness,  $t(120) = 5.72; p < .001$ , Cohen's  $d = 1.09$ , Phoneme elision,  $t(120) = 6.97; p < .001$ , Cohen's  $d = 1.28$ , Rapid automatized naming,  $t(120) = -5.45; p < .001$ , Cohen's  $d = 1.21$ , Oral reading accuracy,  $t(120) = 7.77; p < .001$ , Cohen's  $d = 1.54$ , Orthographic coding,  $t(120) = 5.5; p < .001$ , Cohen's  $d = 1.04$ , and Verbal-short-term memory,  $t(120) = 5.12; p < .001$ , Cohen's  $d = .88$ . The results for the target reading measures were replicated in Phase 2 and are presented in Table 2.

Due to the high correlations found among the measures of phonological processing a summary variable to represent phonological processing skill was generated. The Z-scores for the phonological variables were averaged to produce a new variable designated PHONOLOGY. The raw scores for the orthographic task were standardized using the same method to produce a variable designated ORTHOGRAPHY. All scores were standardized by using the mean and standard deviation of the overall sample for each of the measures.

### Visual and Sensory Processing Measures

#### Auditory Tasks

There were 86.5% of the control group and 70% of the group with dyslexia who made no catch trial errors at Phase 1 for the 2 Hz FM task. Two children with dyslexia who made more than 25%

TABLE 2  
Mean Score and 95% Confidence Interval for Additional Reading Measures at Phase 1 and Those Repeated at Phase 2

	Control (N = 52)		Dyslexia (N = 70)	
PA (1)	21.2	(20.6–21.8)	18.3	(17.06–19.1)**
PA (2)	21.31	(20.77–21.85)	19.83	(19.22–20.43)*
PE (1)	10.3	(9.6–11.06)	6.9	(6.27–7.58)**
PE (2)	10.75	(10.02–11.48)	7.63	(7.00–8.26)**
RAN (1)	28.08	(25.5–30.6)	42.6	(38.4–46.8)**
DS	53	(45–60)	31	(26–36.9)**
Oral (1)	71	(48–79)	14	(12–16)**
Ortho (1)	60.5	(57.04–63.5)	50.7	(48.6–52.7)**
Ortho (2)	62.15	(60.04–64.25)	49.4	(47.05–51.83)**

Note. The (1) after the variable indicates Phase 1 and the (2) after the variable indicates Phase 2. PA = Phonological Awareness raw score /24; PE = Phoneme Elision raw score /15; RAN = Rapid Automatized Naming mean response time (sec); DS = Digit Span (Verbal short-term memory) percentile rank; Oral = oral reading percentile rank; Ortho = orthographic coding raw accuracy score /80. \*\* $p < .0005$ .

errors were excluded from the sample. A significant Spearman rank order correlation was found between catch trial performance and threshold sensitivity,  $r_s = .24, p = .008$ . At Phase 2 catch trial errors were less than 6% in each of the groups, and no significant correlation was found between catch trial errors and sensitivity,  $r_s = .01, p = .48$ . In the 240 Hz FM condition, at Phase 1 less than 10% catch trial errors were made by either group and at Phase 2 one child with dyslexia made a single catch trial error only. No significant correlations were found between group or sensitivity thresholds for the 240 Hz FM stimuli.

All assumptions of the 2 (Phase) by 2 (group) mixed ANOVA were met for analysis of the 2 Hz FM data. The dyslexia group were significantly less sensitive than the control group,  $F(1, 118) = 9.38, p = .003$ . This effect was found at Phase 1 ( $M_{dyslexia} = 2.29, SD = 1.05; M_{control} = 1.94, SD = .80$ ),  $F(1, 118) = 3.98, p = .048$ , Cohen's  $d = .37$ , and at Phase 2,  $F(1, 118) = 12.04, p = .001$ , Cohen's  $d = .72$ . ( $M_{dyslexia} = 2.00, SD = 0.79; M_{control} = 1.57, SD = .55$ ). There was a significant main effect of threshold estimate,  $F(1, 118) = 15.91, p < .001$ . Both groups were more sensitive at Phase 2 when compared to Phase 1. No significant interaction was found between testing phase and reader group,  $F(1, 118) = 0.33, p = .556$ .

Following a square root transformation of the 240 Hz FM thresholds to stabilize the variance in the distributions all assumptions of the mixed ANOVA were met. There was a significant main effect of reader group,  $F(1, 120) = 10.33, p = .002$ , with the dyslexia group less sensitive than the control group at Phase 1 ( $M_{dyslexia} = 2.05, SD = .81; M_{control} = 1.57, SD = .55$ ),  $F(1, 120) = 11.28, p = .001$ , Cohen's  $d = .62$ , and at Phase 2, ( $M_{dyslexia} = 0.114, SD = .10; M_{control} = 0.087, SD = .13$ ),  $F(1, 120) = 4.10, p = .046$ , Cohen's  $d = .37$ . There was a significant main effect of testing phase,  $F(1, 120) = 21.65, p < .001$ , with both groups more sensitive at Phase 2 testing. There was no significant interaction found between threshold estimate and reader group,  $F(1, 120) = 2.83, p = .10$ .

### *Motion Sensitivity*

There were less than 8% of participants from either group who made catch trial errors on the global motion task at either testing phase. After exclusion of one child with dyslexia who made 25% catch trial errors at Phase 1, there was no significant influence of the catch trial errors on motion sensitivity or group at either testing phase.

Following a square root transformation of the global motion thresholds to stabilize the variance in the distributions all assumptions of the 2 (threshold estimate) by 2 (group) mixed ANOVA were met. Overall the dyslexia group were significantly less sensitive than the control group to global motion,  $F(1, 119) = 10.78, p = .001$ . The dyslexia group were significantly less sensitive at Phase 1,  $F(1, 119) = 11.21, p = .001$ , Cohen's  $d = .62$  ( $M_{dyslexia} = 9.10%; SD = 3.8; M_{control} = 6.94%; SD = 3.0$ ), and at phase 2,  $F(1, 119) = 4.73, p = .032$ , Cohen's  $d = .42$ , ( $M_{dyslexia} = 6.37%; SD = 2.9; M_{control} = 5.24%; SD = 2.4$ ). There was a significant effect of testing phase, with increased global motion sensitivity found at Phase 2 when compared to Phase 1,  $F(1, 119) = 58.4, p < .001$  for both groups. No significant interaction was found between reader group and testing phase,  $F(1, 119) = 2.09, p = .15$ .

### Temporal Stability of the Temporal Processing Measures

Difference scores were obtained to evaluate the change in sensitivity for each of the sensory measures at each testing phase. Prior to assessing temporal stability, children with difference scores on

the sensory measures of more than 3 standard deviations from the mean difference were removed as extreme scores. In the 2 Hz FM condition, 2 children with dyslexia had extreme scores. In the 240 Hz FM condition, 4 children, 2 children with dyslexia and 2 children from the control group were removed. On the global motion task, 4 children, 3 with dyslexia, were excluded from these analyses.

Intraclass correlation coefficients (ICC) were generated to measure the temporal stability of the sensory thresholds. These were generated in two ways. First, threshold agreement was obtained by determining whether the thresholds were the same for each child at each threshold estimate. Second, the consistency of measurement was obtained across time. In the 2 Hz FM condition, the interclass correlation for agreement was .70 (95% CI .53 to .80) and for consistency, .72 (95% CI .60 to .80). In the 240 Hz FM condition, the intraclass correlation for agreement was .59 (95% CI .29 to .75), and for consistency was .65 (95% CI .49 to .76). For the global motion task the intraclass correlation for agreement was .66 (95% CI .12 to .84) and for consistency, .76 (95% CI .65 to .85). In all cases the ICCs for agreement were poorer than the ICCs for consistency, and importantly the 95% confidence limits were substantially wider, showing a high level of variability in the estimates obtained. The guidelines used to evaluate the strength of the ICCs for agreement have suggested that an ICC below .4 represents poor agreement and that ICCs between .40 and .59 represent moderate agreement. ICCs between .60 and .75 represent good agreement, with ICCs above .75 representing excellent agreement (McDowell, 2006). While the ICCs generated for agreement were in the moderate to good range, the wide confidence intervals produced suggest that agreement for each of the measures can range from poor to excellent. The variability found can partially be explained by the systematic increase in sensitivity found on each of the sensory processing measures from Phase 1 to Phase 2 of the study.

The repeatability of the sensory sensitivity thresholds for the auditory and visual processing tasks was further evaluated by comparing the level of agreement or repeatability of each of these measures from Phase 1 to Phase 2. The mean difference in sensitivity is generated by subtracting sensitivity at Phase 2 from sensitivity at Phase 1. The mean and the standard deviation of the difference score provide an estimate of the measurement error found (Bland & Altman, 1999). The estimate of sensory sensitivity used is the mean of the Phase 1 and Phase 2 sensitivity thresholds (Bland & Altman, 1986). Both measures are used to generate a graphical representation that shows whether measurement error changes across the range of sensitivity scores obtained. In addition, the 95% limits of agreement are generated by adding and subtracting twice the difference standard deviation from the mean difference scores ( $M \text{ difference} \pm 2SD$ ). Difference scores that are either greater or smaller than these limits are considered outliers. When the level of agreement is high, no systematic pattern is found between the mean sensitivity and the difference scores. In addition, the difference scores should be clustered around a difference score of 0. The wider the 95% limits of agreement, the poorer the agreement obtained.

For each of the auditory and visual tasks the mean difference scores were greater than 0, showing that on average sensitivity increased from Phase 1 to Phase 2. Figure 2 shows the level of agreement for the 2 Hz FM data. No specific pattern was found between sensitivity and difference scores, however, there were a number of outlying scores. These scores mainly represented children from the dyslexia and control groups with much greater sensitivity at Phase 2 than at Phase 1. In contrast, the extreme scores found for the 240 Hz FM condition (see Figure 3), appeared to be children (mainly from the dyslexia group) who performed with greater variability, with some having poorer sensitivity at Phase 2 and others having better sensitivity at Phase 2. The wide 95% lim-

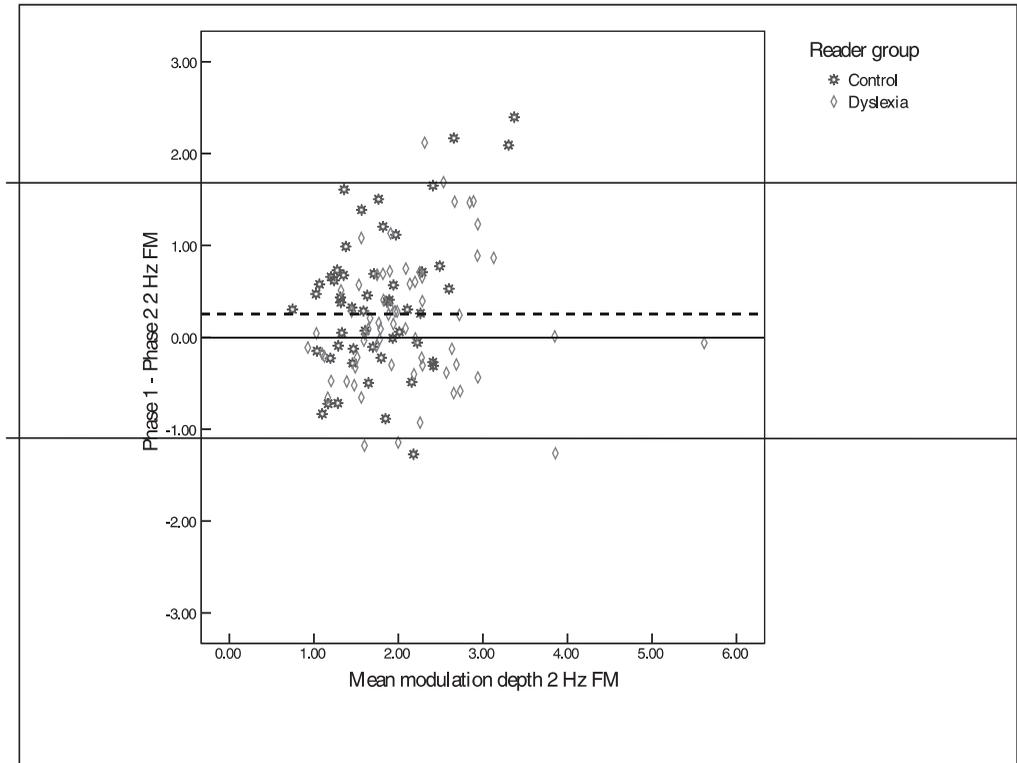


FIGURE 2 Plot for level of agreement for 2 Hz FM. Mean sensitivity difference score and mean sensitivity scores for Phase 1 and Phase 2 were used. The superimposed lines represent the 95% limits of agreement (Upper Limit [UL] = 1.71 and Lower Limit [LL] = -1.191).

its for agreement found for both auditory tasks corresponds to the wide confidence intervals obtained for the ICCs for agreement. Figure 4 shows the level of agreement plot for the global motion task. Consistent with the auditory 2 Hz FM tasks, no systematic pattern is observed between the mean sensitivity and difference scores. However, the 95% level of agreement span is wide showing poor agreement at Phase 1 and Phase 2. Most children falling outside the 95% levels of agreement have substantially increased sensitivity on the motion task at Phase 2, with the majority of these children members of the dyslexia group.

### Deviance Analysis

The proportion of children with dyslexia and sensory processing deficits was determined using deviance analysis (Ramus et al., 2003). The threshold sensitivity used to determine the presence of a sensory deficit was 1.65 standard deviations (one tail 95% confidence interval) above the control group mean, after children from the control group with extreme scores were removed from the sample. There were 23% (17) of the group with dyslexia with a sensory deficit on the 2 Hz FM task at Phase 1 and 28.5% (20) with a deficit at Phase 2. There were 15% (10) of the dyslexia

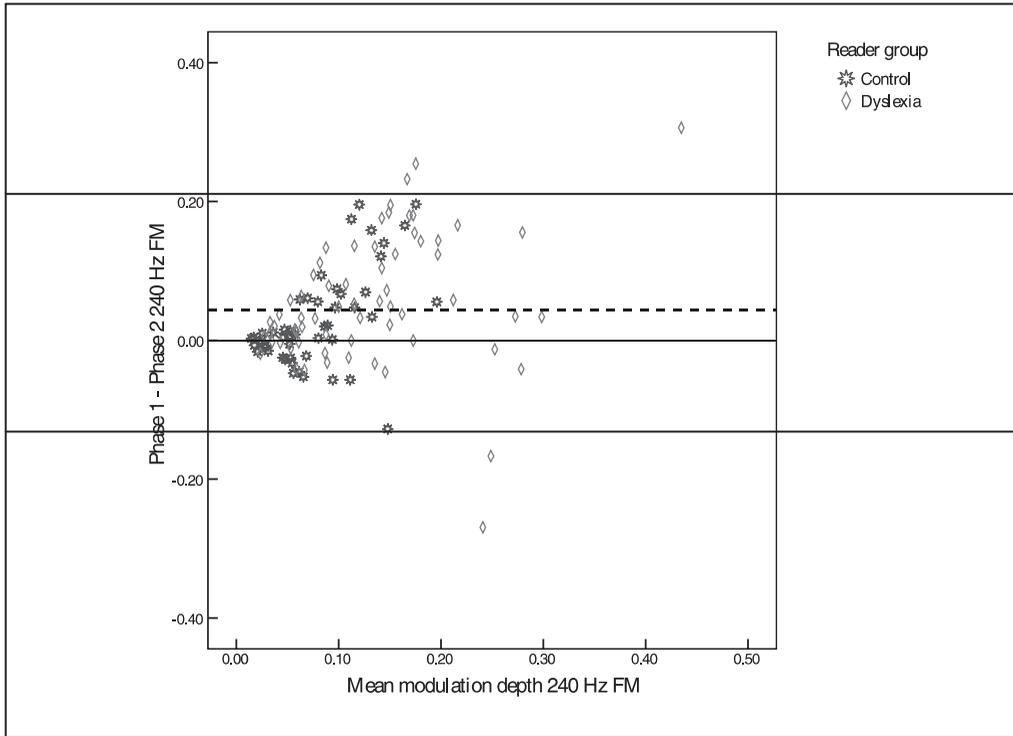


FIGURE 3 Plot for level of agreement for 240 Hz FM. Mean sensitivity difference score and mean sensitivity scores for Phase 1 and Phase 2 were used. The superimposed lines represent the 95% limits of agreement (Upper Limnit [UL] = .21 and Lower Limit [LL] = -.12). The dashed line represents the mean difference score.

group with a deficit at both testing phases. The majority of children with a deficit at one testing phase were at least one standard deviation less sensitive than the control group at the alternative phase of testing, showing a pattern of generally reduced sensitivity. There were 61.4% (43) of the dyslexia group without a deficit at either phase.

At 240 Hz FM, 34% (24) of the children with dyslexia had a deficit at Phase 1 and 28.5% (20) had a deficit at Phase 2. There were 22.8% (16) with a deficit on this measure at both phases. Children with dyslexia found to have a deficit at one testing phase but not the other were generally variable in sensitivity on the alternative testing phase, with less than half at least one standard deviation less sensitive than the control group mean on the alternative testing phase. There were 60% (42) of the dyslexia group who failed to show evidence of a deficit at either testing phase.

On the global motion task, 36.2% (26) of the children with dyslexia had a deficit at Phase 1 and 27% (19) had a deficit at Phase 2. There were 17.1% (12) children with a motion deficit at both testing phases. All children with dyslexia who had a global motion deficit at Phase 2 and not at Phase 1 were at least one standard deviation less sensitive than the control group mean at Phase 1 testing, showing that reduced sensitivity was a general characteristic of the motion deficit group at Phase 2. The children with a deficit at Phase 1 and not at Phase 2 were more variable in their per-

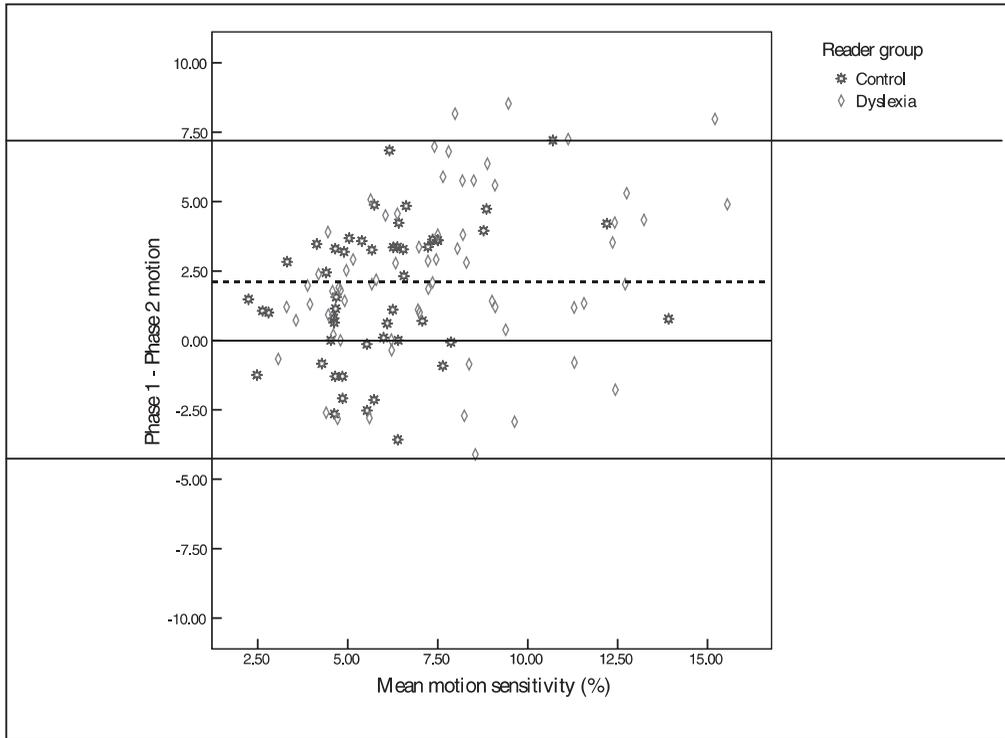


FIGURE 4 Plot for level of agreement for global motion sensitivity. Mean sensitivity difference score and mean sensitivity scores for Phase 1 and Phase 2 were used. The superimposed lines represent the 95% limits of agreement UL = 7.38% and LL = -3.32%. The dashed line represents the mean difference score.

formance, with few showing evidence a generally reduced sensitivity. There were 52.8% (37) of the children with dyslexia who did not have a motion deficit at either phase.

#### Effects of Sensory Deficits on Cognitive and Reading Skills

Independent groups *t*-tests compared the performance of children with dyslexia, with or without sensory deficits on PHONOLOGY, ORTHOGRAPHY, short-term verbal memory, and non-verbal ability. The alpha level of rejection was reduced from .05 to .0125 to account for Type 1 errors. The results found in Table 3 show that children with a deficit on the 2 Hz FM stimulus were significantly less sensitive on the measure of PHONOLOGY at Phase 1,  $t(68) = 3.26, p = .002$ ; Cohen's  $d = .94$ , but not at Phase 2. No other significant effects were found using this measure at either Phase 1 or Phase 2. The groups with or without a deficit on the 240 Hz FM stimuli did not differ significantly on any cognitive measure at either testing phase.

Children with a motion deficit were significantly less accurate on measures of PHONOLOGY at Phase 1,  $t(67) = 2.23, p = .002$ ; Cohen's  $d = .85$ , and Phase 2,  $t(68) = 3.13, p = .003$ , Cohen's  $d = .85$ ; ORTHOGRAPHY at Phase 1,  $t(67) = 3.36, p = .001$ , Cohen's  $d = .85$  and Phase 2,  $t(68) = 3.83, p < .001$ , Cohen's  $d = 1.05$ , and verbal short term memory at Phase 1,  $t(67) = 3.47, p = .001$ , Co-

TABLE 3  
Means Standard Deviations and the Results of Independent Groups *t*-Test Analyses on Children With Dyslexia With or Without Sensitivity Deficits, on Cognitive and Reading Measures

	Phase 1		Phase 2	
2 HZ FM	<i>Deficit</i> (N = 16)	<i>No Deficit</i> (N = 54)	<i>Deficit</i> (N = 20)	<i>No Deficit</i> (N = 50)
Phonology	-.549 (.46)*	-.109 (.48)	-.238 (.61)	-.142 (.48)
Orthography	-.475 (.97)	-.361 (.75)	-.464 (.81)	-.504 (.95)
Short-term Memory	-.797 (.97)*	-.235 (.82)	-.425 (1.0)	-.339 (.84)
Ability	101.1 (8.7)	102.4(8.8)	100.0 (8.0)	102.89 (8.9)
240 HZ FM	<i>Deficit</i> (N = 22)	<i>No Deficit</i> (N = 47)	<i>Deficit</i> (N = 20)	<i>No Deficit</i> (N = 50)
Phonology	-.284 (.46)	-.173 (.53)	-.201 (.38)	-.157 (.57)
Orthography	-.604 (.64)	-.22 (.90)	-.628 (.84)	-.438 (.94)
Short-term Memory	-.657 (.78)	-.33 (.90)	-.482 (.81)	-.316 (.91)
Ability	99.93 (7.9)	103.1 (9.0)	100.1 (5.8)	102.89 (9.6)
Motion Sensitivity	<i>Deficit</i> (N = 26)	<i>No Deficit</i> (N = 42)	<i>Deficit</i> (N = 19)	<i>No Deficit</i> (N = 51)
Phonology	-.450 (.44)*	-.066 (.50)	-.469 (.58)*	-.058 (.44)
Orthography	-.605 (.64)*	-.281 (.85)	-1.12 (.87)*	-.260 (.82)
Short-term Memory	-.657 (.78)*	-.22 (.90)	-.939 (.87)*	-.149 (.79)
Ability	99.9 (7.8)	103.2 (9.0)	100.2 (7.6)	102.8 (9.1)

*Note.* Phonology, orthography, and short-term memory are standardized Z scores. Ability score is the standardized Ravens Colored Progressive Matrices score.

\**p* < .05.

hen’s *d* = .88 and Phase 2, *t*(68) = 3.61, *p* = .001, Cohen’s *d* = .98. No significant group differences were found on non-verbal ability at either testing phase.

### Associations Between Sensory Processing, and Cognitive Measures

The associations between the psychoacoustic variables, coherent motion, the ORTHOGRAPHY and PHONOLOGY measures, and non-verbal ability were obtained for the variables at each testing phase. These correlations, presented in Table 4, show low to moderate linear correlations between the psychoacoustic variables, global motion, and cognitive variables for the sample at Phase 1. These findings are consistent with the correlations reported in previous studies (Talcott et al., 1999; Talcott, Witton, et al., 2000; Talcott et al., 2002; Witton et al., 1998, 2002). In addition to external replication of previous research, the current study replicated the results internally by demonstrating that similar weak to moderate correlations could be found at retesting nine months later (Phase 2), *r* = .25–.42.

Separate hierarchical multiple regression analyses were performed at Phase 1 and at Phase 2 to determine the extent that the measures of sensory sensitivity could account for phonological and orthographic skills. The standardized PHONOLOGY and ORTHOGRAPHY measures were used as the dependant variables. Non-verbal ability, age, and catch trial performance were entered at Step 1 to control for development, ability, and vigilance. In the analyses of auditory sensory processing both the 2 and 240 Hz FM stimuli were entered at Step 2 of the analysis to control for shared task demands. In a separate analysis coherent motion sensitivity was entered at Step 2. Summary results are presented in Table 5.

TABLE 4  
Correlations (Pearson's *r*) Between Study Measures at Phase 1 (*N* = 122)

	<i>P</i>	<i>O</i>	<i>IQ</i>	<i>CM</i>	<i>2 Hz</i>
Phase 1					
PHONOLOGY (P)					
ORTHOGRAPHY (O)	.59**				
IQ	.31**	.32**			
Coherent motion (CM)	-.39**	-.38**	-.32**		
2 Hz FM (2 Hz)	-.42**	-.21**	-.37**	-.21**	
240 Hz FM	-.31**	-.35**	-.32**	.23**	.20*
Phase 2					
PHONOLOGY (P)					
ORTHOGRAPHY (O)	.49**				
IQ	.23**	.38**			
Coherent motion (CM)	-.39**	-.45**	-.16		
2 Hz FM (2 Hz)	-.30**	-.25	-.25**	-.09	
240 Hz FM	-.28**	-.22**	-.23**	.20*	.14

Note. \*\**p* < .01; \**p* < .05.

TABLE 5  
Data From Regression Analysis Predicting Participant's Scores on Composite Standardized  
Phonology and Orthography Measure at Phase 1 and Phase 2 for the Total Sample (*N* = 122)

	<i>Phase 1</i>	<i>Phase 2</i>
Phonology		
2 and 240 Hz FM entered at Step 2	<i>R</i> <sup>2</sup> at Step 1 = .298*** <i>R</i> <sup>2</sup> <i>chg</i> Step 2 = .114*** 2 Hz FM = .098*** 240 Hz FM = .012	<i>R</i> <sup>2</sup> at Step 1 = .194*** <i>R</i> <sup>2</sup> <i>chg</i> at Step 2 = .072** 2 Hz FM = .060** 240 Hz FM = .010
Motion Sensitivity entered at step 2		
<i>Overall Sample</i>	<i>R</i> <sup>2</sup> at Step 1 = .266*** <i>R</i> <sup>2</sup> <i>chg</i> Step 2 = .064***	<i>R</i> <sup>2</sup> at Step 1 = .202*** <i>R</i> <sup>2</sup> <i>chg</i> at Step 2 = .039*
Orthography		
2 and 240 Hz FM entered at Step 2	<i>R</i> <sup>2</sup> at Step 1 = .426*** <i>R</i> <sup>2</sup> <i>chg</i> Step 2 = .017 2 Hz FM = .010 240 Hz FM = .006	<i>R</i> <sup>2</sup> at Step 1 = .393*** <i>R</i> <sup>2</sup> <i>chg</i> at Step 2 = .030 2 Hz FM = .028* 240 Hz FM = .002
Motion Sensitivity entered at step 2		
<i>Overall Sample</i>	<i>R</i> <sup>2</sup> at Step 1 = .400*** <i>R</i> <sup>2</sup> <i>chg</i> Step 2 = .047**	<i>R</i> <sup>2</sup> at Step 1 = .377*** <i>R</i> <sup>2</sup> <i>chg</i> at Step 2 = .040**

Note. \**p* < .05; \*\**p* < .01; \*\*\**p* < .001.

When entered at Step 2 of the analysis sensitivity to 2 and 240 Hz FM accounted for an additional 11.7% of the variance in PHONOLOGY at Phase 1,  $F(2,114) = 11.39$ ,  $p < .001$ . Sensitivity to 2 Hz FM only made a significant unique contribution, accounting for 9.8% of the variance,

$t(114) = 4.39, p < .001$ . At Phase 2 an additional 7.2% of the variance in PHONOLOGY was accounted for by the psychoacoustic variables,  $F(2,115) = 5.63, p = .005$ . The 2 Hz FM stimulus only uniquely accounted for a significant 6% of the variance,  $t(115) = 3.07, p = .003$ . When ORTHOGRAPHIC coding was used as the dependent variable, sensitivity to 2 and 240 Hz FM when entered at Step 2 accounted for no additional variance at Phase 1,  $F(1, 114) = 1.75, p = .178$ , or at Phase 2,  $F(1, 115) = 3.01, p = .053$ .

When entered at Step 2 motion sensitivity accounted for an additional 6.4% of the variance in PHONOLOGY at Phase 1,  $F(1,115) = 11.02, p = .001$ , and for an additional 3.9% of the variance in PHONOLOGY at Phase 2,  $F(1,116) = 5.98, p = .016$ . When the same analysis was conducted using ORTHOGRAPHY as the dependent variable, motion sensitivity when added at Step 2 accounted for a further 4.7% of the variance at Phase 1,  $F(1,115) = 10.11, p = .002$ , and 4% of the variance at Phase 2,  $F(1, 116) = 8.09, p = .005$ .

## DISCUSSION

The primary aim of the current study was to determine if the reduced sensitivity to measures of auditory and visual processing that had been found by previous studies in groups with dyslexia (e.g., Talcott et al., 2003; Witton et al., 1998) could be replicated externally and internally across time. The prevalence of deficits on psychophysical measures in individual participants was also investigated, as was the temporal stability of those deficits. The association of those deficits to specific cognitive processes was also measured. The implications for visual and auditory temporal processing explanations of dyslexia are discussed.

### Auditory and Visual Sensory Deficits in Children With Dyslexia

On the auditory sensory processing measures the group with dyslexia were significantly less sensitive than the control group to the 2 and 240 Hz FM stimuli at both testing phases. While the 2 Hz FM task was used as a measure of auditory temporal processing, the 240 Hz FM task was included as a control task to provide an index of general task-specific variance in participants' performance. In general, it has similar task demands to the 2 Hz FM task, while tapping different sensory mechanisms. These results fail to support the findings of previous studies that have reported temporal specific deficits in adults using the same tasks (Witton et al., 1998, 2002). One explanation for the discrepancies reported concerns the power of the different studies. The current study had power of  $\sim .89$ , while the Witton et al. (2002) study that used the same auditory tasks had lower power ( $\delta = .44$ ). The effect sizes reported for the between groups effect for the 240 Hz FM stimulus in Witton et al was Cohen's  $d = .59$ , similar to the effect size found at Phase 1 in the current study. One conclusion that could be reached from these auditory findings that is consistent with some previous studies is that children with dyslexia have a general deficit in auditory processing (Bretherton & Holmes, 2003; Goswami et al., 2002; Hill et al., 1999; Nittrouer, 1999; Share, Jorm, MacLean, & Matthews, 2002; Waber et al., 2001).

However, the general deficits on the auditory processing measures found in this study may have occurred because of difficulties with shared task demands across the temporal and non-temporal auditory tasks. In the correlation analyses significant associations were found between sensitivity to the 240 Hz FM stimulus and orthographic and phonological processes. However, when the task

demands shared by the two auditory tasks were controlled in the regression analyses, the 240 Hz FM stimulus failed to account for unique variance in either cognitive process; results that replicate previous findings (Talcott, Witton, et al., 2000). The significant contribution made by sensitivity to the 2 Hz FM, but not the 240 Hz FM stimulus to the explanation of the phonological processing variable at both phases of the study is consistent with previous reports (Talcott et al., 1999, 2002).

Consistently reduced sensitivity to global motion was also found for the dyslexia group at Phase 1 and Phase 2, replicating previous results in children that have used the same global motion task (Solan et al., 2004, 2007; Talcott et al., 2003). In addition, sensitivity to global motion accounted for significant variance on both phonological and orthographic processing tasks after vigilance, age, and ability were controlled at both phases of the study. These findings replicate the associations found previously between global motion sensitivity and these cognitive processes (Cornelissen et al., 1998; Ben-Shachar, Dougherty, Deutsch, & Wandell 2007; Talcott, Witton, et al., 2000; Talcott et al., 2002).

Based on the between-group differences and the associations found between the cognitive sub-skills of reading and sensory sensitivity, the current data provide support for the previously reported associations found between visual and auditory sensory processes and some reading skills. However, the deviance analysis produced evidence that auditory and visual sensory deficits were evident in between 22%–36% of the dyslexia group when single threshold estimates were used. This finding is consistent with previous reports (Edwards et al., 2004; Pellicano & Gibson, 2008; Witton et al., 1998).

Children with a global motion deficit at Phase 1 or Phase 2 also had poorer accuracy on measures of phonological processing, orthographic coding, and on verbal short-term memory than other children with dyslexia. These findings are consistent with research that has used subgroups of individuals defined by poor orthographic and phonological processing skills (Borsting et al., 1996; Johnson et al., 2008; Slaghuis & Lovegrove, 1985; Slaghuis & Ryan, 1999, 2006), and is also consistent with the results of an fMRI investigation that reported a high correlation between activity at MT on a motion processing task and performance on a phonological processing task (Ben-Shachar et al., 2007). Together these results suggest that there are a group of individuals with dyslexia and a global motion deficit, who are less skilled when processing phonological and orthographic information, and have poorer short-term verbal memory than other children with dyslexia.

The deviance analyses results for the 2 Hz FM stimulus were less consistent. Children with a deficit at Phase 1 were significantly poorer on the phonological measures than children with dyslexia and no deficit, but this result was not replicated at Phase 2. Task difficulty may have contributed. In this study the dyslexia group were significantly less sensitive to both the temporal and non-temporal acoustic measures, which suggests that the general difficulty when performing the task may have contributed to the effects found. On the global motion task, stimuli were presented for over 2 seconds; however, the stimulus duration for the auditory measures were 1 second only. While producing adequate sensitivity in adolescent (Huslander et al., 2004) and adult groups (Witton et al., 2002), with children the short stimulus duration may have produced inconsistencies. The effects of temporal stability, maturation, and task demands discussed in following sections may have contributed.

### Temporal Stability of the Auditory and Visual Sensory Measures

The inconsistent findings for the sensory measures may also be partially explained by the poor temporal stability found with measures of the intraclass correlations for agreement and consis-

tency and on the level of agreement plots. This error was demonstrated by the generally low ICC and by the large variation in the 95% limits of agreement (Bland & Altman, 1999). Poor agreement is partially explained by the increase in sensitivity across time for each of the sensory measures. The restricted range of threshold sensitivity scores producing relatively large measurement errors with small threshold changes may also contribute, particularly when assessing sensory sensitivity in children.

Poor vigilance that produces lapses in concentration in children with dyslexia is one explanation for the measurement error found in this study (Stuart et al., 2001; Williams et al., 2003). Catch trial errors influenced both dyslexia and control groups equally, suggesting that lapses in concentration influence measurement consistency in all children. The reduction in catch trial errors across testing phases, particularly for the 2 Hz FM condition, suggested that increased task familiarity, even after 9 months, contributed to greater efficiency among all children. The significant increase in sensitivity found on each of the measures and the positive bias found in the level of agreement analysis supports this suggestion.

The use of the weighted adaptive staircase technique may have also contributed to the measurement error found. Methodologically, the weighted adaptive staircase used in this study, produced a 75% level of accuracy (Kaernbach, 1991). One important advantage of this technique is its ability to rapidly obtain threshold estimates. While it has been criticized for overestimating sensitivity (Leek, 2001), this method reduces the difficulties children may have with lapses in concentration and fatigue; issues that can occur when a large number of trials may be required to reach threshold. The large step size used may have contributed to the error found, and this explanation has been used previously to explain non-significant results when contrast sensitivity has been measured in dyslexia and control groups (Slaghuis & Ryan, 2006). While the groups with dyslexia were significantly less sensitive on the sensory measures used, the variability in the proportion of children with a consistent deficit across time may have been influenced by the sensitivity of the adaptive technique. On each of the tasks, most children found to have a deficit at Phase 2, were at least one standard deviation less sensitive than the control group mean at Phase 1, suggesting that greater sensitivity in the measurement on the sensory tasks may have produced more consistent evidence of deficits in many children.

In addition to increases in task familiarity, maturation of the visual and auditory systems in the participants may have contributed to the increased sensitivity found at Phase 2 (Bishop & McArthur, 2005; Braddick et al., 2003; Peiffer, Friedman, Rosen, & Fitch, 2004). Full maturation of the dorsal visual pathway occurs when children are between 8 and 10 years of age (Braddick et al., 2003) and in the auditory cortex by 11 to 12 years of age (Moore, 2002). As the age range of children in this study was from 6 to 11 years, some performance improvement may be attributed to maturation of the visual and auditory systems. The effects of maturation may have been greater in children for measurement of the auditory sensory thresholds where poorer consistency was found in the associations between reading sub-skills and sensitivity. Difficulties produced by the task demands may have produced greater non-temporal processing difficulties in the still maturing auditory system.

### Explanations for Heterogeneity in Visual or Auditory Sensory Processing

Given the possible existence of multiple etiological factors, cognitive deficits, and behavioral subtypes it is reasonable to speculate that the 20%–30% of individuals with dyslexia have a sensory

processing deficit that may constitute a separate or additional risk factor for reading failure. Alternatively, this sub-group may have one or more co-morbid disorders that escaped detection in this study or the co-morbid disorders may exist at a sub-clinical level. While care was taken to exclude children with formal diagnoses of other developmental disorders such as ADHD, autism, or dyspraxia, no formal assessment was conducted on the remaining children who may have had sub-clinical level symptomatology of other disorders. While sensory deficits have been found in children with developmental disorders such as autism and dyspraxia where word-level reading disability was not present or had not been assessed (Gunn et al., 2002; Sigmundsson, Hansen, & Talcott, 2003; Pellicano & Gibson, 2008; White, Frith, et al., 2006), the co-morbid presence of these disorders does not explain the associations found between cognitive sub-skills of reading and sensory sensitivity.

Some studies have suggested that sensory processing deficits in individuals with dyslexia occur because of difficulties within a short-term or working memory buffer that provides a vehicle to perform executive processes on information (Slaghuis, Lovegrove, & Davidson, 1993; Slaghuis & Ryan, 1999). The current data demonstrated that the dyslexia group had poorer verbal short-term memory and phonological processing skills than the control group, with the most severe deficits seen in children with a global motion deficit. A recent modification to the phonological deficit hypothesis of dyslexia, which previously attributed these deficits to poorly defined phonological representations (Snowling, 2000), has implicated a working memory buffer (Ramus & Szenkovitis, 2008). More specifically, it has been proposed that individuals with dyslexia may have difficulty accessing and copying phonological representations to and from a phonological working memory buffer for the purposes of performing the various executive processes required by phonological awareness, memory, naming, and reading tasks. Ramus and Szenkovitis have proposed that the neural substrate of these executive processes has common central (frontal) components, which are unaffected in dyslexia, and are partly distributed in each sensory modality and functional module. Therefore, individuals with dyslexia may have a common cognitive deficit that affects access to certain representations and adversely affects some executive processes. In the majority of individuals with dyslexia, this deficit may be expressed in only one domain: the phonological. In up to 30% of those with dyslexia, the deficit may extend across several domains (including auditory and visual), hence the small but consistent relationships found between reading and sensory processing in this and other studies. The range of deficits seen in individuals may depend on the spatial extent of their cortical dysfunctions (Ramus, 2004) and on the type and demands of the tasks presented.

The processing demands required when performing psychophysical tasks, and not the temporal or dynamic nature of the stimulus, have also been used to explain reduced sensitivity found in dyslexia groups (Ahissar, 2007; Banai & Ahissar, 2006; Ben-Yehudah & Ahissar, 2004; Ben-Yehudah, Sackett, Malchi-Ginzberg, & Ahissar, 2001). The deficits are particularly evident when tasks require comparison of two or more stimuli separated by a temporal interval. The conclusion is that the deficit lies in a failure to form a perceptual anchor against which subsequent stimuli can be compared (Ahissar, Lubin, Putter-Katz, & Banai, 2006). The group with dyslexia may have difficulty accessing and copying a well-defined sensory representation of test stimuli to a domain specific (auditory or visual) working memory buffer. The data from the auditory tasks presented in this study support these findings. All of the current tasks, both visual and auditory, required not only processing of the specific aspects of the stimulus, but also access to a well-defined sensory representation within a working memory buffer to allow the executive process of stimulus com-

parison to occur. A deficit in accessing or even creating this representation in a short-term buffer may explain the findings in the current study of general, rather than temporal specific, auditory and visual deficits in the dyslexia group.

## CONCLUSION

In demonstrating that previous findings of relationships between sensory processing skills and reading can be replicated both externally and internally, the current study has added important new evidence to the validity of these findings. However, the findings diverge from previous studies that have used the same auditory tasks in that general, rather than specific temporal deficits were observed. It is proposed that difficulties with cognitive demands common to both the temporal 2 Hz FM and non-temporal 240 Hz FM task may explain the current data in children between 6 and 11 years of age. The divergence from previous studies (Witton et al., 2002) may be explained by the effects of maturation, greater task demands for children and poor temporal stability. Replicating these data and determining what leads to poor performance across a range of psychophysical tasks will be an important avenue for future research.

While significant between-groups effects were found consistently across time, the deviance analysis indicated that sensory deficits existed only in sub-groups of children with dyslexia. While sensory deficits in the visual and auditory domains may be the results of specific dysfunction in the visual and auditory temporal processing systems, these deficits may also be a component of a wider deficit in accessing sensory representations within working memory; a deficit that exists only in the phonological domain in many children with dyslexia. A major challenge for future research will be to explain why sensory deficits appear to exist in only a sub-group of individuals with dyslexia. Development of tasks with high temporal stability that can also accommodate normal changes that occur with maturation and that can control for the non-temporal effects of task demands are critical for future development in this research area.

## ACKNOWLEDGMENTS

The authors thank Professor John Stein, Dr. Caroline Witton, Dr. Peter Hansen, and Dr. Joel Talcott from the Department of Physiology at Oxford University for providing the auditory and visual tasks used in this study. Dr. Caroline Witton wrote the software for the auditory task and Dr. Peter Hansen the motion coherence task. The authors also thank Dr. Franck Ramus for his valuable discussion on his phonological access hypothesis.

## REFERENCES

- Ahissar, M. (2007). Dyslexia and the anchoring-deficit hypothesis. *Trends in Cognitive Science*, *11*, 458–465.
- Ahissar, M., Lubin, Y., Putter-Katz, H., & Banai, K. (2006). Dyslexia and the failure to form a perceptual anchor. *Nature Neuroscience*, *9*, 1558–1564.
- Banai, K., & Ahissar, M. (2006). Auditory processing deficits in dyslexia: Task or stimulus related? *Cerebral Cortex*, *16*, 1718–1728.

- Ben-Shachar, M., Dougherty, R. F., Deutsch, G. K., & Wandell, B. A. (2007). Contrast responsivity in MT+ correlates with phonological awareness and reading measures in children. *Neuroimage*, *37*, 1396–1406.
- Ben-Yehudah, G., & Ahissar, M. (2004). Sequential spatial frequency discrimination is consistently impaired among dyslexic adults. *Vision Research*, *44*, 1047–1063.
- Ben-Yehudah, G., Sackett, E., Malchi-Ginzberg, L., & Ahissar, M. (2001). Impaired temporal contrast sensitivity in dyslexics is specific to retain-and-compare paradigms. *Brain*, *124*, 1381–1395.
- Bishop, D. M. V., & McArthur, G. M. (2005). Individual differences in auditory processing in specific language impairment: A follow-up study using event related potentials and behavioural thresholds. *Cortex*, *41*, 327–341.
- Boets, B., Wouters, J., van Wieringen, A., & Ghesquiere, P. (2006). Auditory temporal information processing in preschool children at family risk of dyslexia: Relations with phonological abilities and developing literacy skills. *Brain and Language*, *97*, 64–79.
- Bland, J., & Altman, D. (1986). Statistical methods for assessing agreement between two methods of clinical measurement. *Lancet*, *i*, 307–310.
- Bland, J., & Altman, D. (1999). Measuring agreement in method comparison studies. *Statistical Methods in Medical Research*, *8*, 135–160.
- Borsting, E., Ridder III, W. H., Dideck, K., Kelley, C., Matsui, L., & Motoyama, J. (1996). The presence of a magnocellular deficit depends on the type of dyslexia. *Vision Research*, *36*, 1047–1053.
- Braddick, O., Atkinson, J., & Wattam-Bell, J. (2003). Normal and anomalous development of visual motion processing: Motion coherence and dorsal stream vulnerability. *Neuropsychologia*, *41*, 1769–1784.
- 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.
- Byrne, B., & Fielding-Barnsley, R. (1989). Phonemic awareness and letter knowledge in the child's acquisition of the alphabetic principle. *Journal of Educational Psychology*, *81*, 805–812.
- Cohen, J. (1990). Things I have learned (so far). *American Psychologist*, *45*, 1304–1312.
- Conlon, E., Sanders, M., & Zapart, S. (2004). Temporal processing in poor adult readers. *Neuropsychologia*, *42*, 142–157.
- 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*, *10*, 1483–1493.
- Cornelissen, P. A., Hansen, P., Gilchrist, I., Cormack, F., Essex, J., & Frankish, C. (1998). Coherent motion detection and letter position encoding. *Vision Research*, *38*, 2181–2191.
- Cornelissen, P. A., Hansen, P., Hutton, J. L., Evangelinou, V., & Stein, J. F. (1998). Magnocellular visual function and children's single word reading. *Vision Research*, *38*, 471–482.
- Demb, J. B., Boynton, G. M., Best, M., & Heeger, D. J. (1998). Psychophysical evidence for a magnocellular pathway deficit in dyslexia. *Vision Research*, *38*, 1555–1559.
- Demb, J. B., Boynton, G. M., & Heeger, D. J. (1998). Functional magnetic imaging of early visual pathways in dyslexia. *The Journal of Neuroscience*, *18*, 6939–6951.
- Drullman, R., Festen, J. M., & Plomp, R. (1994). The effect of temporal envelope smearing on speech reception. *Journal of the Acoustical Society of America*, *95*, 1053–1064.
- Eden, G. F., VanMeter, J. W., Rumsey, J. M., Maisog, J. M., Woods, R. P., & Zeffiro, T. A. (1996). Abnormal processing of visual motion in dyslexia revealed by functional brain imaging. *Nature*, *382*, 66–69.
- Edwards, V. T., Giaschi, D. E., Dougherty, R. F., Edgell, D., Bjornson, B. H., Lyons, C., et al. (2004). Psychophysical indexes of temporal processing abnormalities in children with developmental dyslexia. *Developmental Neuropsychology*, *25*, 321–354.
- Enns, J. T., & Rensinck, R. A. (1992). *V Scope: General purpose tachistoscope for Macintosh*. Vancouver, CA: Micropsych Software.
- Fawcett, A. J., & Nicholson, R. I. (1996). *The Dyslexia Screening Test*. London: The Psychological Corporation.
- Felmingham, K. L., & Jakobson, L. S. (1995). Visual and visuomotor performance in dyslexic children. *Experimental Brain Research*, *106*, 467–474.
- Galaburda, A., & Livingstone, M. (1993). Evidence for a magnocellular deficit in developmental dyslexia. In P. Tallal, A. M. Galaburda, R. R. Llinas, & C. von Euler (eds.), *Temporal information processing in the nervous system: Special reference to dyslexia and aphasia* (Annals of the New York Academy of Sciences, *82*, pp. 71–82). New York: New York Academy of Sciences.
- Goswami, U., Thomson, J., Richardson, U., Stainthorp, R., Hughes, D., Rosen, S., & Scott, S. K. (2002). Amplitude envelope onsets and developmental dyslexia: A new hypothesis. *Proceedings of the National Academy of Sciences*, *99*, 10911–10916.

- Gunn, A., Cory, E., Atkinson, J., Braddick, O., Wattam-Bell, J., Guzzetta, A., & Cioni, G. (2002). Dorsal and ventral stream sensitivity in normal development and hemiplegia. *Neuroreport*, *13*, 843–847.
- Halliday, L. F., & Bishop, D. V. M. (2006). Is poor frequency modulation detection linked to literacy problems? A comparison of specific reading disability and mild to moderate sensorineural hearing loss. *Brain and Language*, *97*, 200–213.
- Hansen, P. C. (2001). *Global form and global motion processing programs*. Department of Physiology, Oxford University.
- Hansen, P. C., Stein, J. F., Orde, S. R., Winter, J. L., & Talcott, J. B. (2001). Are dyslexics' visual deficits limited to measures of dorsal stream function? *NeuroReport*, *12*, 1527–1530.
- Hari, R., Saaskilahti, A., Helenius, P., & Uutela, K. (1999). Non-impaired phase locking in dyslexic adults. *NeuroReport*, *10*, 2347–2348.
- Hatcher, P. (2000). *Sound linkage: An integrated program for overcoming reading difficulties*. London: Whurr.
- Hayduk, S., Bruck, M., & Cavanagh, P. (1996) Low-level visual processing skills of adults and children with dyslexia. *Cognitive Neuropsychology*, *13*, 975–1015.
- Hill, N. I., Bailey, P. J., Griffiths, Y. M., & Snowling, M. J. (1999). Frequency acuity and binaural masking release in dyslexic listeners. *Journal of the Acoustical Society of America*, *106*, L53–L58.
- Hirsch, I. J. (1959). Auditory perception of temporal order. *Journal of the Acoustical Society of America*, *31*, 759–767.
- Huslander, J., Talcott, J., Witton, C., DeFries, J., Pennington, B., Wadsworth, S., et al. (2004). Sensory processing, reading, IQ, and attention. *Journal of Experimental Child Psychology*, *88*, 274–295.
- Johnson, A., Bruno, A., Watanabe, J., Quansah, B., Patel, N., Dakin, S., & Nishida, S. (2008). Visually-based temporal distortion in dyslexia. *Vision Research*, *48*, 1852–1858.
- Kaernbach, C. (1991). Simple adaptive testing with the weighted up-down method. *Perception and Psychophysics*, *49*, 227–229.
- Kronbichler, M., Hutzler, F., & Wimmer, H. (2002). Dyslexia: Verbal impairments in the absence of magnocellular impairments. *NeuroReport*, *13*, 617–620.
- Kubova, Z., Kuba, M., Peregrin, J., & Novakova, V. (1996). Visually evoked potential evidence for magnocellular system deficit in dyslexia. *Physiological Research*, *45*, 87–89.
- Leek, M. R. (2001). Adaptive procedures in psychophysical research. *Perception & Psychophysics*, *63*, 1279–1292.
- Lehmkuhle, S. M., Garzia, R. P., Turner, L., Hash, T., & Baro, J. A. (1993). A defective visual pathway in children with reading disability. *New England Journal of Medicine*, *328*, 989–996.
- Livingstone, M. S., Rosen, G. D., Drislane, F. W., & Galaburda, A. M. (1991). Physiological and anatomical evidence for a magnocellular deficit in developmental dyslexia. *Proceedings of the National Academy of Sciences of the USA*, *88*, 7943–7947.
- Lovegrove, W. (1993). Do dyslexics have a visual deficit? In S. F. Wright & R. Groner (eds.), *Facets of dyslexia and its remediation* (pp. 33–49). Elsevier Science Publishers.
- Lovegrove, W. J., Martin, F., & Slaghuis, W. (1986). A theoretical and experimental case for a visual deficit in specific reading disability. *Cognitive Neuropsychology*, *3*, 225–267.
- Martin, F., & Lovegrove, W. (1987). Flicker contrast sensitivity in normal and specifically disabled readers. *Perception and Psychophysics*, *16*, 215–221.
- May, J. G., Lovegrove, W. J., Martin, R., & Nelson, P. (1991). Pattern-elicited visual evoked potentials in good and poor readers. *Clinical Vision Science*, *6*, 131–136.
- McGraw, K. O., & Wong, S. P. (1996). Forming inferences about some intraclass correlation coefficients. *Psychological Methods*, *1*, 30–46.
- McDowell, I. (2006). *Measuring health: A guide to rating scales and questionnaires*. New York, NY: Oxford University Press.
- Merigan, W. H., & Maunsell, J. H. (1993). How parallel are the primate visual pathways? *Annual Review of Neuroscience*, *16*, 369–402.
- Merigan, W. H., Katz, L. M., & Maunsell, J. H. (1991). The effects of parvocellular lateral geniculate nucleus lesions on the acuity and contrast sensitivity of macaque monkeys. *Journal of Neuroscience*, *11*, 994–1001.
- Moore, D. R. (2002). Auditory development and the role of experience. *British Medical Bulletin*, *63*, 171–181.
- Moore, B. C. J., & Sek, A. (1995). Effects of carrier frequency, modulation rate, and amplitude waveform on the detection of modulation and the discrimination of modulation type (amplitude modulation versus frequency modulation). *Journal of the Acoustical Society of America*, *97*, 2468–2478.
- Neale, M. D. (1999). *Neale analysis of reading ability* (3rd ed.). Camberwell, Victoria: Australian Council for Educational Research.

- Newsome, W. T., & Pare, E. B. (1988). A selective impairment in motion perception following lesions of the middle temporal visual area (MT). *Journal of Neuroscience*, *8*, 2201–2211.
- Nittrouer, S. (1999). Do temporal processing deficits cause phonological processing problems? *Journal of Speech, Language, and Hearing Research*, *42*, 925–942.
- Olson, R., Forsberg, H., Wise, B., & Rack, J. (1994). Measurement of word recognition, orthographic and phonological skills. In G. Reid Lyon (ed.), *Frames of reference for the assessment of learning disabilities: New views on measurement issues* (pp. 243–278). Baltimore, MD: Brookes.
- Palmer, A. R., & Russell, I. J. (1986). Phase-locking in the cochlear nerve of the guinea pig and its relation to the receptor potential of inner hair-cells. *Hearing Research*, *24*, 1–15.
- Pasquini, E. S., Corriveau, K. H., & Goswami, U. (2007). Auditory processing of amplitude envelope rise time in adults diagnosed with developmental dyslexia. *Scientific Studies of Reading*, *11*, 259–286.
- Peiffer, A. M., Friedman, J. T., Rosen, G. D., & Fitch, R. H. (2004). Impaired gap detection in juvenile microgyric rats. *Brain Research: Developmental Brain Research*, *152*, 93–98.
- Pellicano, E., & Gibson, L. Y. (2008). Investigating the functional integrity of the dorsal visual pathway in autism and dyslexia. *Neuropsychologia*, *46*, 2593–2596.
- Ramus, F., & Szenkovitis, G. (2008). What phonological deficit. *Quarterly Journal of Experimental Psychology*, *61*, 129–141.
- Ramus, F. (2004). Neurobiology of dyslexia? A reinterpretation of the data. *Trends in Neurosciences*, *27*, 720–726.
- Ramus, F., Rosen, S., Dakin, S. C., Day, B. L., Catelette, J. M., White, S., et al. (2003). Theories of developmental dyslexia: Insights from a multiple case study of dyslexic adults. *Brain*, *126*, 841–865.
- Raven, J. C., Court, J. H., & Raven, J. (1995). *Coloured progressive matrices*. Oxford, UK: Oxford Psychologists Press.
- Raymond, J. E., & Sorensen, R. E. (1998). Visual motion perception in children with dyslexia: Normal detection but abnormal integration. *Visual Cognition*, *5*, 389–404.
- Richardson, U., Thomson, J. M., Scott, S. K., & Goswami, U. (2004). Auditory processing skills and phonological representation in dyslexic children. *Dyslexia*, *10*, 215–233.
- Rosen, S. (2003). Auditory processing in dyslexia and specific language impairment: Is there a deficit? What is its nature? Does it explain anything? *Journal of Phonetics*, *31*, 509–527.
- Shaywitz, S., Escobar, M., Shaywitz, B., Fletcher, J., & Makugh, R. (1992). Evidence that dyslexia may represent the lower tail of a normal distribution of reading ability. *New England Journal of Medicine*, *326*, 145–150.
- Schiller, S. M., Logothetis, N. K., & Charles, E. R. (1990). Functions of the colour-opponent and broad-band channels of the visual system. *Nature*, *343*, 68–70.
- Shamma, S. (2003). Physiological foundations of temporal integration in the perception of speech. *Journal of Phonetics*, *31*, 495–501.
- Shannon, R. V., Zeng, F. G., Kamath, V., Wygonski, J., & Ekelid, M. (1995). Speech recognition with primarily temporal cues. *Science*, *270*, 303–304.
- Share, D. L., Jorm, A. F., MacLean, R., & Matthews, R. (2002). Temporal processing and reading disability. *Reading and Writing: An Interdisciplinary Journal*, *15*, 151–178.
- Sigmundsson, H., Hansen, P. C., & Talcott, J. B. (2003). Do ‘clumsy’ children have visual deficits? *Behavioural Brain Research*, *139*, 123–129.
- Slaghuis, W. L. (2007). Letter to the editor. *Vision Research*, *47*, 1976–1978.
- Slaghuis, W. L., & Lovegrove, W. (1984). Flicker masking of spatial-frequency-dependent visible persistence and specific reading disability. *Perception*, *13*, 527–534.
- Slaghuis, W. L. & Lovegrove, W. J. (1985). Spatial-frequency, dependent visible persistence and specific reading disability. *Brain and Cognition*, *4*, 219–240.
- Slaghuis, W. L., Lovegrove, W. J., & Davidson, J. A. (1993). Visual and language processing deficits are concurrent in dyslexia. *Cortex*, *29*, 601–615.
- Slaghuis, W. L., & Ryan, J. F. (2006). Directional motion contrast sensitivity in developmental dyslexia. *Vision Research*, *46*, 3291–3303.
- Slaghuis, W. L., & Ryan, J. F. (1999). Spatio-temporal contrast sensitivity, coherent motion, and visible persistence in developmental dyslexia. *Vision Research*, *39*, 651–668.
- Snowling, M. J. (2000). *Dyslexia*. Oxford, UK: Blackwell.
- Solan, H. A., Shelley-Tremblay, J. F., Hansen, P. C., & Larson, S. (2007). Is there a common linkage among reading comprehension, visual attention, and magnocellular processing? *Journal of Learning Disabilities*, *40*, 270–278.

- Solan, H. A., Shelley-Tremblay, J., Hansen, P. C., & Larson, S. (2004). M-cell deficit and reading disability: A preliminary study of the effects of temporal vision processing therapy. *Optometry: Journal of the American Optometric Association*, 75, 640–650.
- Stein, J. (2001). The magnocellular theory of developmental dyslexia. *Dyslexia*, 7, 12–36.
- Stein, J., & Walsh, V. (1997). To see but not to read: The magnocellular theory of dyslexia. *Trends in Neurosciences*, 20, 147–152.
- Stuart, G. W., McAnally, K. I., & Castles, A. (2001). Can contrast sensitivity functions in dyslexics be explained by inattention rather than a magnocellular deficit? *Vision Research*, 41, 3205–3211.
- Talcott, J. B., Hansen, P. C., Assoku, E. L., & Stein, J. F. (2000). Visual motion sensitivity in dyslexia: Evidence for temporal and energy integration deficits. *Neuropsychologia*, 38, 935–943.
- Talcott, J. B., Hansen, P. C., Willis-Owen, C., McKinnell, I. W., Richardson, A. J., & Stein, J. F. (1998). Visual magnocellular impairment in adult developmental dyslexics. *Neuro-Ophthalmology*, 20, 187–201.
- 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.
- Talcott, J. B., Witton, C., McLean, M., Hansen, P. C., Rees, A., Green, G. G. R., & Stein, J. F. (1999). Can sensitivity to auditory frequency modulation predict children's phonological and reading skills? *NeuroReport*, 10, 2045–2050.
- Talcott, J. B., Gram, A., Van Ingelghem, M., Witton, C., Stein, J. F., & Egil Toennesen, F. (2003). Impaired sensitivity to dynamic stimuli in poor readers of a regular orthography. *Brain and Language*, 87, 259–266.
- Talcott, J. B., Witton, C., Hebb, G. S., Stoodley, C. J., Westwood, E. A., France, S. J., et al. (2002). On the relationship between dynamic visual and auditory processing and literacy skills: Results from a large primary school study. *Dyslexia*, 8, 204–225.
- Tallal, P. (1980). Auditory temporal perception, phonics, and reading disabilities in children. *Brain and Language*, 9, 182–198.
- Vellutino, F. R., Fletcher, J. M., Snowling, M. J., & Scanlon, D. M. (2004). Specific reading disability (dyslexia): What have we learned in the past four decades? *Journal of Child Psychology and Psychiatry*, 45, 2–40.
- Vellutino, F. R., Scanlon, D. M., Sipay, E. R., Small, S. G., Pratt, A., Chen, R., et al., (1996). Cognitive profiles of difficult-to-remediate and readily remediated poor readers: Early intervention as a vehicle for distinguishing between cognitive and experiential deficits as basic causes of specific reading disability. *Journal of Educational Psychology*, 88, 601–638.
- Waber, D. P., Weiler, M. D., Wolff, P. H., Bellinger, D., Marcus, D. J., Arel, R., Forbes, P., & Wypij, D. (2001). Processing of rapid auditory stimuli in school age children referred for evaluation of learning disorders. *Child Development*, 72, 37–49.
- Wechsler, D. (2003). *The Wechsler intelligence scale for children—fourth edition*. San Antonio, TX: The Psychological Corporation.
- White, S., Frith, U., Milne, E., Rosen, S., Swettenham, J., & Ramus, F. (2006). A double dissociation between sensorimotor impairments and reading disability: A comparison of autistic and dyslexic children. *Cognitive Neuropsychology*, 23, 748–761.
- White, S., Milne, E., Rosen, S., Hansen, P. C., Swettenham, J., Frith, U., & Ramus, F. (2006). The role of sensorimotor processing in dyslexia: A multiple case study of dyslexic children. *Developmental Science*, 9, 237–255.
- Williams, M. J., Stuart, G. W., Castles, A., & McAnally, K. I. (2003). Contrast sensitivity in subgroups of developmental dyslexia. *Vision Research*, 43, 467–477.
- Wilmer, J. B., Richardson, A. J., Chen, Y., & Stein, J. F. (2004). Two visual motion processing deficits in developmental dyslexia associated with different reading skills deficits. *Journal of Cognitive Neuroscience*, 16, 1–13.
- Witton, C. (2002). *Programs for generating auditory 2 Hz FM and 240 Hz FM stimuli*. Laboratory of Professor John Stein, Department of Physiology, Oxford University.
- Witton, C., Stein, J. F., Stoodley, C. J., Rosner, B. S., & Talcott, J. B. (2002). Separate influences of acoustic AM and FM sensitivity on the phonological decoding skills of impaired and normal readers. *Journal of Cognitive Neuroscience*, 14, 866–874.
- Witton, C., Talcott, J. B., Hansen, P. C., Richardson, A. J., Griffiths, T. D., Rees, A., et al. (1998). Sensitivity to dynamic auditory and visual stimuli predicts nonword reading ability in both dyslexic and normal readers. *Current Biology*, 8, 791–797.
- Woodcock, R. W. (1997). *Woodcock Diagnostic Reading Battery*. Itasca, IL: Riverside Publishing.
- Yule, W., Rutter, M., Berger, M., & Thompson, B. (1973). Over and under achievement in reading. *British Journal of Educational Psychology*, 44, 1–12.