Perception & Psychophysics
2007, 69 (8), 1344-1359

The contribution of rapid visual and auditory processing to the reading of irregular words and pseudowords presented singly and in contiguity

Agnes Au
James Cook University, Cairns, Australia

and

Bill Lovegrove
University of Southern Queensland, Toowoomba, Australia

This study examined the relative involvement of rapid auditory and visual temporal resolution mechanisms in the reading of phonologically regular pseudowords and English irregular words presented both in isolation and in contiguity as a series of six words. Seventy-nine undergraduates participated in a range of reading, visual temporal, and auditory temporal tasks. The correlation analyses suggested a general timing mechanism across modalities. There were more significant correlations between the visual temporal measures and irregular word reading and between the auditory measures and pseudoword reading. Auditory gap detection predicted pseudoword reading accuracies. The low temporal frequency flicker contrast sensitivity measure predicted the accuracies of isolated irregular words and pseudowords presented in contiguity. However, when a combined speed–accuracy score was used, visible persistence at both low and high spatial frequencies and auditory gap detection were active the in the reading of pseudowords presented in contiguity. Sensory processing skills in both visual and auditory modalities accounted for some of the variance in the reading performance of normal undergraduates, not just reading-impaired students.

Many dyslexic and language-impaired participants are impaired in processing sensory events that require precise timing (Heath, Hogben, & Clark, 1999; Tallal, Stark, & Mellits, 1985; Witton et al., 1998). Since dyslexics are less accurate and slower in detecting the temporal gap that differentiates pairs of patterns presented visually, auditorily, cross-modally (Laasonen, Service, & Virsu, 2002; Meyler & Breznitz, 2005), or intramodally (Rose, Feldman, Jankowski, & Futterweit, 1999), a general temporal deficit across modalities is documented (Becker, Elliott, & Lachman, 2005; Galaburda & Livingstone, 1993; Solan, 2004).

In vision, disabled readers are less sensitive to moving stimuli (Cornelissen & Hansen, 1998; Schulte-Körne, Deimel, Bartling, & Remschmidt, 2004; Solan, Hansen, Shelley-Tremblay, & Ficarra, 2003; Talcott et al., 2003; Talcott et al., 2002; Talcott et al., 2000; Wilmer, Richardson, Chen, & Stein, 2004). They perform poorly on visual temporal order judgment (TOJ) (Cacace, McFarland, Ouimet, Schrieber, & Marro, 2000; May, Williams, & Dunlap, 1988). Poor readers also display longer visible persistence at low spatial frequencies (Lovegrove, Heddle, & Slaghuis, 1980; Slaghuis & Lovegrove, 1985), as well as higher gap detection or temporal integration thresholds to visual stimuli presented in rapid succession (Boden & Brodeur, 1999; Martos & Marmolejo, 1993). Although many dyslexic adults and children demonstrate a loss of contrast sensitivity to low spatial frequency and/or high temporal frequency visual stimuli under mesopic, but not photopic, luminance conditions (Cornelissen, Richardson, Mason, Fowler, & Stein, 1995; Demb, Boynton, Best, & Heeger, 1997; Edwards et al., 2004; Gross-Glenn et al., 1995), results in contrast sensitivity studies are less conclusive for the visual defect (Williams, Stuart, Castles, & McAnally, 2003).

In audition, reading-disabled adults and children experience difficulties discriminating the pattern of presentation of tone triads with short durations (Walker, Shinn, Cranford, Givens, & Holbert, 2002), rapidly presented speech sounds (Kraus et al., 1996), and amplitude-modulated (AM) or frequency-modulated (FM) tones (McAnally & Stein, 1996; Witton, Stein, Stoodley, Rosner, & Talcott, 2002). They also display higher fusion points to separate two auditory temporal stimuli (Hari & Kiesilä, 1996; Hautus, Setchell, Waldie, & Kirk, 2003; McCroskey & Kidder, 1980). Poor readers take longer or make more errors when judging the order of two auditory stimuli presented in rapid succession (Heiervang, Stevenson, & Hugdahl, 2002; Mody, Studdert-Kennedy, & Brady, 1997).

Similarly, mixed results have been found regarding whether auditory temporal processing is related to lan-

A. Au, agnes.au@jcu.edu.au

guage impairment and what type of auditory processes are relevant to phonological and language processing. Ahissar, Protopapas, Reid, and Merzenich (2000) showed that poor readers had poor auditory processing abilities only in tasks that required spectral distinctions, such as tone frequency discrimination. The impairment was more pronounced when the stimuli were presented in brief forms and in rapid succession. Although dyslexics reportedly discriminate auditory frequency poorly, deficits are found only in tasks that employ a traditional two-interval *same–different* paradigm, and not in tasks that employ multiple exposures per trial to the standard stimulus (France et al., 2002). Witton et al. (2002) found that dyslexics were less sensitive to 2-Hz FM and 20-Hz AM tones, but not to 2-Hz AM tones. Thresholds on 2-Hz FM and 20-Hz AM tones were more strongly associated with pseudoword accuracy. Accordingly, dyslexics do not have a general deficit in detecting all slow modulations. Ben-Yehudah, Banai, and Ahissar (2004) showed that the reading-disabled were impaired in discriminating the frequency of two tones presented with short, but not long, interstimulus intervals (ISIs). However, they had no difficulty discriminating the timing of tone sequences at short ISIs (McAnally, Castles, & Bannister, 2004). Hence, tone duration also plays a role in discrimination, apart from ISIs. McArthur and Bishop (2001) commented that performance on psychophysical tests of rapid auditory processing can confound with other task-related factors, such as attention, memory, learning, and stimulus classification.

The ability to track brief, rapidly successive frequency changes within the acoustic waveform of speech (formant transitions) (Kelly, Rooney, & Phillips, 1996; Tallal, 2003) is crucial to speech discrimination (Phillips & Farmer, 1990). In fact, auditory TOJ and temporal acuity are related to phonological synthesis (Laasonen et al., 2002) and reading development. However, a general auditory temporal deficit is not sufficient to explain reading difficulties (Studdert-Kennedy & Mody, 1995) because significant differences are likely to be found in verbal, as opposed to nonverbal, stimuli (Boden & Brodeur, 1999; Breier, Gray, Fletcher, Foorman, & Klaas, 2002; Mody et al., 1997; Schulte-Körne, Deimel, Bartling, & Remschmidt, 1999; see also Denenberg [1999] for his critique on Mody et al. [1997] and Studdert-Kennedy, Mody, & Brady's [2000] response to Denenberg [1999]).

One controversial issue in the literature is how temporal processing is related to reading impairment. It is widely accepted that phonological deficits constitute the core deficit of reading disabilities, whereas temporal processing has only a distal influence. Ramus (2004) argued that specific phonological deficits in reading disability can occur with an optional concomitant sensorimotor syndrome because impairment of temporal input is not sufficient to explain developmental reading difficulties (Laasonen et al., 2002). For instance, some reading-disabled children with early temporal deficits are no less proficient on later phonological and reading measures than are those without early temporal impairment (Share, Jorm, Maclean, & Matthews, 2002). Failure in rapid auditory processing, such as poor tone order discrimination, does not necessarily result in deficits associated with the processing of speech sounds and phonological or phoneme awareness (Bretherton & Holmes, 2003; Nittrouer, 1999; Studdert-Kennedy, 2002). There is a lack of relationship between the severity of auditory and of language impairment in the reading-disabled group. Thus, auditory deficits are not causally related to reading disability but, rather, are only associated with reading disability (Rosen, 2003).

On the other hand, some studies have posited a potential causal influence of temporal processing on subsequent phonological development because the temporal deficit exists before children learn to read (Benasich & Tallal, 1996; Facoetti & Lorusso, 2000). Both visual and auditory temporal abilities predict subsequent language skills development (Benasich & Tallal, 2002; Hood & Conlon, 2004; Lyytinen et al., 2005; Rose et al., 1999; Share et al., 2002; Trehub & Henderson, 1996). Nevertheless, the timing tasks share little variance with phonological sensitivity and contribute little unique variance to word reading (Chiappe, Stringer, Siegel, & Stanovich, 2002).

Whereas most of the studies have focused on the temporal deficits in disabled readers, the relationship between temporal processing and normal reading has seldom been investigated. This is particularly obvious when normal adult readers and different formats of word presentation are considered. One of the few exceptions is Chase, Ashourzadeh, Kelly, Monfette, and Kinsey (2003). They investigated the effect of color on text processing in normal adult readers. As a matter of fact, dyslexia may represent the lower end of an undemarcated continuum of reading ability and is not distinct from normal reading with respect to some reading, cognitive, and temporal processes (Au & Lovegrove, 2001b; Conlon, Sanders, & Zapart, 2004). Consequently, this study investigated the possibility of a generalized timing mechanism and how well the rapid visual and auditory processes accounted for different reading tasks in a normal college sample.

We aimed to investigate, first, whether there was a generalized timing mechanism across vision and audition. We expected some correlations between the visual and the auditory temporal tasks if a generalized timing mechanism existed.

Second, we examined the relative involvement of the auditory and visual temporal processes in the reading of irregular words and phonologically regular pseudowords presented singly and in contiguity as a series of six words in normal readers. This area has been slightly overlooked, especially when the reading of irregular words and pseudowords requires the visual and the grapheme–phoneme conversion routes, respectively, of the *dual-route* reading mechanisms (Coltheart, Rastle, Perry, Langdon, & Ziegler, 2001). Likewise, irregular words are more likely to associate with visual temporal processes, whereas pseudowords are more likely to associate with auditory temporal processes (Au & Lovegrove, 2001a; Booth, Perfetti, MacWhinney, & Hunt, 2000; Talcott et al., 2000). Hence, we anticipated a closer relationship between the auditory temporal processes and the reading of pseudowords. In contrast, irregular words would be related more to the visual temporal processes.

Third, we examined how well various visual processes accounted for the reading of isolated words and words presented in contiguity. Several studies have demonstrated that rapid visual processing is relevant to the reading of whole text. To illustrate, disabled readers find it more difficult to read a whole line of text (Hill & Lovegrove, 1993). Poor visual temporal processors find it easier to process single words than whole text (Pammer, Lavis, & Cornelissen, 2004). Cornelissen and Hansen (1998) suggested that visual temporal processes define letter position, so that accurate visual coding is required to identify a word in terms of its letter positions before the graphemes, phonemes, and pronunciation are retrieved (Stein, 2003; Stein & Talcott, 1999). Meanwhile, visual temporal processes also take part in whole-word pattern recognition, in the processing of the low spatial frequency components of text (Chase et al., 2003), and in visual attention when whole text is read (Pammer et al., 2004). Therefore, we anticipated a differential relationship between various visual processes and the reading of words presented singly and in contiguity. More specifically, we wanted to examine whether visual temporal measures with certain temporal or spatial frequency conditions (Burr, Morrone, & Ross, 1994; Livingstone & Hubel, 1988) were related more to certain word presentation formats.

METHOD

Participants

Seventy-nine English-speaking undergraduate psychology students (18–54 years of age, comprising 65 females and 14 males) were offered bonus points to participate in the study. They had normal or corrected-to-normal vision and normal hearing. They had no known history of epilepsy, migraine headache, ear infections, or reading disability. The sample size was based on the number of visual and auditory variables used for subsequent statistical analyses (Tabachnick & Fidell, 2001).

Tests

This study adopted the visual and auditory tests that have been most commonly used and shown to be reliable in assessing the temporal processes in the literature. Poor readers are impaired at flicker contrast sensitivity (FSEN), visual TOJ (VTOJ), visible persistence (based on the judgment of a blank [BLAN] or a flicker [FLICK]), the flicker fusion task from Chase and Jenner (1993) (CHAS), auditory gap detection (AGAP), and auditory TOJ (ATOJ). Ideally, we wanted to include a motion study and a nontemporal isoluminant task as a control task. Since the instruments required for these tasks were unavailable at time of testing, we could run only FSEN, VTOJ, visible persistence, and CHAS tasks, with restrictions on certain parameters. For example, for FSEN, we could monitor only the temporal frequency from 2 to 12 Hz, where 12 Hz should be more sensitive than 2 Hz for assessing the visual temporal processes. Similarly, for VTOJ, visible persistence, and CHAS, spatial frequencies of 2 c/d or below were better than spatial frequencies of 7 c/d or above for assessing the temporal function. McArthur and Bishop (2001) recommended the use of tests that take into account the relationship between low-level nonverbal, verbal, and various reading abilities. Therefore, irregular words and phonologically regular pseudowords were presented singly and in contiguity (Measure 3) to assess participants' reading ability. We also used AGAP of noise (nonverbal) and ATOJ of tones. The latter may share some characteristics with speech stimuli in frequency and pitch dimension (Measure 2). Table 1 summarizes the function of the tasks. Details of the tasks will be given below.

The experiments were undertaken with the understanding and written consent of each participant according to the guidelines of the human research ethics committee at the University. There were four experimental sessions. The first session consisted of the Advanced Raven's Progressive Matrices (IQ) test (Raven, 1962), which measures nonverbal reasoning skills in adults and word-reading tasks. The second session consisted of the FSEN task. The third session consisted of the VTOJ, the AGAP, and the ATOJ tasks. The last session consisted of the visible persistence task based on the judgment of a blank (BLAN) and flicker (FLICK), respectively, and the CHAS tasks. Test conditions were counterbalanced within each session.

Measure 1a: Flicker Contrast Sensitivity

Apparatus and Stimuli.The task measured the participants' contrast threshold of a sinusoidally flickering field that lasted for 1 sec. The field was presented at a 5º visual angle and was viewed binocularly at a distance of 57 cm from a Tektronix 608 *x–y* display. An Innisfree Picasso CRT Image Generator generated the fields on the *x–y* display with a P31 phosphor. Contrast thresholds were measured using Wetherill and Levitt's (1965) up–down threshold reversal method with a two-alternative forced choice paradigm (converging on an accuracy of 79% correct trials). Time-averaged luminance was held constant at 10.3 cd/m^2 across all temporal frequency and contrast changes. The room illumination was less than 1 cd/m^2.

Procedure. The participants were instructed to fixate on the circular field and to report on which interval (whether 1 or 2) the flickering, rather than a blank field, was presented. One field was presented in the first interval, followed by the other in the second interval. Each interval was signaled by a beep. Accuracy was emphasized, and so the participant's response time was relatively less important to the task. Feedback and practice were given. The order of presentation for the 2- and 12-Hz conditions was counterbalanced.

Measure 1b: Visual Temporal Order Judgment

Apparatus and Stimuli. This test measured the minimum stimulus onset asynchrony (SOA) required to report the order of two 200-msec vertical sinusoidal gratings generated in two circles, each with a diameter of 3.2 cm, presented 1º on either side of the fixation point. The experimental settings were the same as those in the FSEN task. The stimulus contrast was 0.3. The average luminance of the surround and the space-average luminance of the screen of the *x–y* display were held constant at 30 cd/m^2 across all spatial frequency changes. The background illumination was less than 1 cd/m^2.

Procedure. With binocular viewing, the participants were instructed to fixate on the fixation point after a tone had been presented on each trial. They had to indicate whether the first grating appeared on the left or on the right circle as accurately and as quickly as possible. Accuracy was of top priority, and thus, the participants' response latencies were of little importance to this experiment. Feedback and practice were given. The dependent variable was the participants' SOA and was recorded using Wetherill and Levitt's (1965) up–down threshold reversal method with a two-alternative forced choice paradigm (converging on an accuracy of 79% correct trials). Counterbalancing the conditions, the participants had to respond to gratings both of 1 and 7 c/d.

Measure 1c: Visible Persistence Based on the Judgment of a Blank or a Flicker

Apparatus and Stimuli. The test measured the participant's ability to detect a gap within alternating vertical square wave gratings of spatial frequencies of 2 and 12 c/d. The stimuli completely filled a 6.74º × 4.53º target field and were presented via a tachistoscope at a binocular viewing distance of 129 cm. On each trial, the gratings were presented for 200 msec, and were alternated with a variable blank ISI for 10 cycles. The duration of the blank ISI was

Table 1
Summary of the Visual, Auditory, Reading, and IQ Tasks

Task	Task Name	Unit Measured	Processes Measured
FSEN2	Flicker contrast sensitivity at 2 Hz	contrast threshold	visual temporal process
FSEN12	Flicker contrast sensitivity at 12 Hz	contrast threshold	visual temporal process
VTOJ1	Visual temporal order judgment at 1 c/d	SOA (msec)	visual temporal process
VTOJ7	Visual temporal order judgment at 7 c/d	SOA (msec)	visual temporal process
BLAN2	Visible persistence (based on the judgment of a blank) at 2 c/d	ISI (msec)	visual temporal process
BLAN12	Visible persistence (based on the judgment of a blank) at 12 c/d	ISI (msec)	visual temporal process
FLICK2	Visible persistence (based on the judgment of a flicker) at 2 c/d	ISI (msec)	visual temporal process
FLICK12	Visible persistence (based on the judgment of a flicker) at 12 c/d	ISI (msec)	visual temporal process
CHAS2	Flicker fusion at 2 c/d	stimulus duration (msec)	visual temporal process
CHAS12	Flicker fusion at 12 c/d	stimulus duration (msec)	visual temporal process
AGAP15	Auditory gap detection at 15 msec	ISI (msec)	auditory temporal process
AGAP100	Auditory gap detection at 100 msec	ISI (msec)	auditory temporal process
ATOJ15	Auditory temporal order judgment at 15 msec	SOA (msec)	auditory temporal process
ATOJ75	Auditory temporal order judgment at 75 msec	SOA (msec)	auditory temporal process
ATOJ200	Auditory temporal order judgment at 200 msec	SOA (msec)	auditory temporal process
ISA	Irregular words accuracy, single condition	accuracy (%)	reading processes (more involved with the visual temporal processes)
IST	Irregular words reaction time, single condition	latency (msec)	reading processes (more involved with the visual temporal processes
ICA	Irregular words accuracy, contiguity condition	accuracy (%)	reading processes (more involved with the visual temporal processes)
ICT	Irregular words reaction time, contiguity condition	latency (msec)	reading processes (more involved with the visual temporal processes)
PSA	Phonologically regular pseudowords accuracy, single condition	accuracy (%)	reading processes (more involved with the auditory temporal processes)
PST	Phonologically regular pseudowords reaction time, single condition	latency (msec)	reading processes (more involved with the auditory temporal processes)
PCA	Phonologically regular pseudowords accuracy, contiguity condition	accuracy (%)	reading processes (more involved with the auditory temporal processes)
PCT	Phonologically regular pseudowords reaction time, contiguity condition	latency (msec)	reading processes (more involved with the auditory temporal processes)
IQ	Advanced Raven's Progressive Matrices	standard scores	nonverbal reasoning skills

the dependent variable and was recorded using a random staircase method. The luminance was held constant at 4.8 cd/m^2 across all spatial frequency changes.

Procedure. In the BLAN condition, in which visible persistence was measured on the basis of the judgment of a blank field, the participants had to report the presence or absence of a clear blank interval between the gratings in the grating–blank–grating cycle that repeated 10 times. Accuracy, rather than response latency, was stressed. The participants were given practice and had to respond to both spatial frequencies of 2 and 12 c/d. The order of presentation for both conditions was counterbalanced.

In the FLICK condition, in which visible persistence was measured on the basis of the judgment of a flicker within the gratings, the participants were instructed to report the presence or the absence of a flicker, rather than a blank, between the gratings. The experimental procedure was the same as that in the BLAN condition.

Measure 1d: Flicker Fusion

This task was adopted from Chase and Jenner (1993) and measured the minimum stimulus duration required to perceive the alternation of a vertical and a horizontal square wave grating as a stable, nonflickering *checkerboard*. In order to distinguish it from the visible persistence task that involved the use of flicker (i.e., Measure 1c), we denoted the task with the abbreviation *CHAS*.

Apparatus and Stimuli. The apparatus was the same as that employed in the visible persistence tasks. The vertical and horizontal square wave gratings were presented alternately for 3 sec via the tachistoscope controlled by an IBM-compatible computer and C programs, so that the two gratings superimposed with each other to form a checkerboard. The luminance was held constant at 5 cd/m^2 across all spatial frequency changes.

Procedure. Under binocular viewing, the participants were instructed to report whether the checkerboard display was flickering or not. Accuracy, rather than response latency, was of major importance. The dependent variable was the mean stimulus duration for each display and was recorded using the random staircase method. Practice was provided. Counterbalancing the conditions, the participants responded to both spatial frequencies of 2 and 12 c/d.

Measure 2a: Auditory Gap Detection of Noise

Apparatus and Stimuli.This test recorded the minimum threshold required to detect a gap between two bursts of noise, with both bursts lasting either 15 or 100 msec. The stimuli were continuous white noise or paired bursts of noise separated by a gap of variable duration (ISI). They were presented through Sony MDR CD250 headphones at 60 dB SPL. A National Semiconductor MM5837 digital noise source and a Realistic STA-76 IC/FET AM/FM stereo receiver were used to generate the noise.

Procedure. Due to difficulty in getting access to the testing facility, no complete audiological examination was carried out. Nevertheless, the participants were presented with three pairs of noise bursts to ensure that they could hear the stimuli properly. On each trial, the participants heard either two small bursts of noise followed by a single burst of noise, or vice versa. They had to indicate at which interval the paired bursts of noise appeared. The mean ISI to distinguish the paired bursts of noise was the dependent variable and was recorded using Wetherill and Levitt's (1965) procedure. Accuracy, rather than reaction time, was emphasized. Feedback and practice were given. The order of presentation for both conditions (15 and 100 msec) was counterbalanced.

Measure 2b: Auditory Temporal Order Judgment

Apparatus and Stimuli.This task recorded the minimum SOA required to detect the order of a high (2200-Hz) and a low (400-Hz) sine wave tone that had a ramped rise/fall time of 5 msec. The duration of the second tone was 15, 75, or 200 msec in different conditions. The duration of the first was equal to the sum of the duration of the second plus the SOA. Two Novatech DDS3 Digital Synthesizer boards in the dual tone generator were used to generate the tones at 60 dB SPL. The equipment was the same as that in the AGAP task.

Procedure. No complete audiological examination was performed because of the difficulty in getting access to the testing facility. Yet, to ensure that the participants had no hearing loss at the frequencies used in the study, they were presented with the tone pair three times and were asked if they heard the stimuli clearly. On each trial, the participants had to determine whether the high or the low tone was presented first. The mean SOA to distinguish the tone order was recorded using Wetherill and Levitt's (1965) procedure. Accuracy, rather than response latency, was of top priority. Feedback and practice were given. Counterbalancing the order of presentation, the participants took part in all the conditions (15, 75, and 200 msec).

Measure 3: Irregular and Phonologically Regular Pseudoword Reading

Apparatus and Stimuli. The task measured the participants' accuracy and latency in reading aloud the irregular words and phonologically regular pseudowords presented both singly and in contiguity on the computer monitor.

Two lists of 30 irregular words and two lists of 30 phonologically regular pseudowords were used (see Appendix A). For the irregular words, 30 were selected from Castles and Coltheart (1993), and 30 were selected from the National Adult Reading Test (NART) (Nelson, 1982). For the phonologically regular pseudowords, 30 were selected from Castles and Coltheart, and 30 were selected from the Woodcock's Reading Mastery Tests–Revised (Woodcock, 1987) and the Woodcock Language Proficiency Battery Test Book (Woodcock, 1984). Both types of words were matched on word and syllable length, and multisyllabic words were used to avoid ceiling effects in adult readers. Only words not exceeding nine characters in length were included, because increased word length may increase the chance of saccades when reading within a single word (Shapiro, Ogden, & Lind-Blad, 1990). The mean word length for the two lists of irregular words was 5.37 and 5.23, respectively, whereas those for the two lists of phonologically regular pseudowords were 5.07 and 4.87, respectively. Due to constraints in matching the word and syllable length, the initial phonemes of the irregular and pseudowords were not matched. The mean frequencies of occurrence of the two lists of irregular words were 45.91 and 34.11 (Baayen, Piepenbrock, & Gulikers, 1995), respectively [$t(29) = 0.57, p > .05$]. The words were counterbalanced across the two modes of presentation, as will be illustrated below.

Procedure. There were two modes of text presentation: single and contiguity. In the former, a single word was presented in the center of the screen on each trial, and the participants had to read it aloud as accurately and as quickly as possible with a microphone. The next word appeared immediately after the voice onset. The presentation used is similar to the rapid serial visual presentation format (Bourne, Young, & Angell, 1986; Juola, Tiritoğlu, & Pleunis, 1995). There were 12 practice trials and 30 experimental trials.

For the contiguity mode of presentation, six crosses were presented evenly from left to right on the screen, subtending a visual angle of 20º between the first and the last crosses. A word appeared below each cross successively on each trial. The participants had to follow the crosses and read the words as accurately and as quickly as possible. To avoid preemptory eye movement, the participants were instructed not to jump to the next cross until the word under that cross appeared. The next word appeared immediately after the voice onset. There were five experimental trials and two practice trials.

Due to individual differences in reading time, stimulus presentation was self-paced, to ensure that the participants had enough time to decipher each word. Self-correction was not allowed, due to technical constraints. Pronunciation accuracy was scored for each word, and the percentage of accuracy for each list (condition) was calculated [(total score/30) × 100%]. Naming latencies (in milliseconds) were recorded as the duration from the beginning of presentation of the word until voice onset was recorded by the microphone.

There were four presentation conditions: irregular words presented singly (IS), irregular words presented in contiguity (IC), phonologically regular pseudowords presented singly (PS), and phonologically regular pseudowords presented in contiguity (PC). The order of presentation was counterbalanced.

RESULTS

A log transformation was performed on the data in order to achieve normal distribution and homogeneous variance for better comparison because the distributions of AGAP15 (AGAP at 15-msec condition) and the ATOJ measures were positively skewed. Also, the distributions of BLAN12 (visible persistence at 12 c/d), AGAP15, ATOJ15 (ATOJ at 15-msec condition) and ATOJ75 (ATOJ at 75-msec condition) were too peaked. All statistical analyses were based on the log-transformed data. The means and standard deviations for the original and the log-transformed visual, auditory, and reading data are shown in Table 2.

Low temporal frequency visual stimuli (2 Hz: 0.047) displayed significantly higher contrast thresholds than did high temporal frequency stimuli (12 Hz: 0.015) [$t(78) = 37.76, p < .0001$]. High spatial frequency visual stimuli (7 c/d: 173.8 msec) displayed significantly longer SOAs than did low spatial frequency stimuli (1 c/d: 55.05 msec) [$t(78) = 23.18, p < .0001$]. The participants needed a significantly shorter stimulus duration at 2 c/d (16.51 msec) than at 12 c/d (23.98 msec) [$t(78) = 21.99, p < .0001$] to perceive the alternation of a vertical and a horizontal square wave grating as a nonflickering checkerboard.

For visible persistence, the main effect of task type [$F(1,78) = 1{,}942.38, p < .0001$] indicated that the ISI based on the judgment of a blank field (BLAN2, 187.88 msec; BLAN12, 281.89 msec) was significantly longer than that based on the judgment of a flicker (FLICK2, 6.84 msec; FLICK12, 15.93 msec). There was a main effect of spatial frequency [$F(1,78) = 367.06, p < .0001$], indicating that the ISI at 2 c/d (BLAN2, 187.88 msec; FLICK2, 6.84 msec) was shorter than that at 12 c/d (BLAN12, 281.89 msec; FLICK12, 15.93 msec).

Table 2
Means (With Standard Deviations) of the Visual, Auditory, and Reading Measures and Their Log-Transformed Data ($N = 79$)

	Original Data		Log-Transformed Data			
Task	*M*	*SD*	*M*	*SD*	Unit	Notes
FSEN2	0.047	0.015	−3.09	0.29	contrast threshold	flicker contrast sensitivity at 2 Hz
FSEN12	0.015	0.003	−4.24	0.24	contrast threshold	flicker contrast sensitivity at 12 Hz
VTOJ1	55.05	23.27	3.92	0.42	msec	visual temporal order judgment at 1 c/d
VTOJ7	173.80	93.55	5.04	0.47	msec	visual temporal order judgment at 7 c/d
BLAN2	187.88	66.54	5.16	0.45	msec	visible persistence (based on the judgment of a blank) at 2 c/d
BLAN12	281.89	103.41	5.58	0.34	msec	visible persistence (based on the judgment of a blank) at 12 c/d
FLICK2	6.84	6.42	1.59	0.79	msec	visible persistence (based on the judgment of a flicker) at 2 c/d
FLICK12	15.93	12.25	2.47	0.81	msec	visible persistence (based on the judgment of a flicker) at 12 c/d
CHAS2	16.51	3.13	2.79	0.17	msec	flicker fusion at 2 c/d
CHAS12	23.98	4.91	3.16	0.20	msec	flicker fusion at 12 c/d
AGAP15	4.01	2.29	1.30	0.40	msec	auditory gap detection at 15 msec
AGAP100	3.01	0.70	1.08	0.20	msec	auditory gap detection at 100 msec
ATOJ15	66.67	67.81	3.86	0.81	msec	auditory temporal order judgment at 15 msec
ATOJ75	85.46	55.69	4.25	0.64	msec	auditory temporal order judgment at 75 msec
ATOJ200	132.09	113.03	4.67	0.64	msec	auditory temporal order judgment at 200 msec
ISA	77.64	10.05	4.34	0.14	%	irregular words accuracy, single condition
ICA	78.99	8.74	4.36	0.11	%	irregular words accuracy, contiguity condition
PSA	84.43	9.60	4.43	0.13	%	phonologically regular pseudowords accuracy, single condition
PCA	83.42	9.50	4.42	0.12	%	phonologically regular pseudowords accuracy, contiguity condition
IST	901.15	268.81	6.76	0.29	msec	irregular words reaction time, single condition
ICT	871.21	279.59	6.73	0.29	msec	irregular words reaction time, contiguity condition
PST	957.44	295.33	6.82	0.29	msec	phonologically regular pseudowords reaction time, single condition
PCT	925.63	273.94	6.79	0.27	msec	phonologically regular pseudowords reaction time, contiguity condition
IQ	110.14	17.08	4.69	0.16	standard scores	nonverbal reasoning skills measured by the Advanced Raven's Progressive Matrices

There was also a significant task × spatial frequency interaction [$F(1,78) = 50.72$, $p < .0001$], indicating that the ISI increase in the BLAN condition was larger across spatial frequency changes.

There was a significant within-subjects effect among the five auditory tasks [$F(4,312) = 1{,}191.45$, $p < .0001$]. A priori contrasts showed that AGAP15 (4.01 msec) was significantly longer than AGAP100 (3.01 msec) [$F(1,78) = 34.34$, $p < .0001$]. ATOJ15 (66.67 msec) was significantly shorter than ATOJ75 (85.46 msec) [$F(1,78) = 33.12$, $p < .0001$] and ATOJ200 (132.09 msec) [$F(1,78) = 165.44$, $p < .0001$]. ATOJ75 was significantly shorter than ATOJ200 [$F(1,78) = 48.46$, $p < .0001$]. In general, the gap detection thresholds were significantly shorter than the TOJ thresholds [$t(78) = 47.3$, $p < .0001$].

A repeated measures ANOVA was performed on reading accuracy and latency separately, using word type (irregular word vs. pseudoword) as one factor and the presentation mode (single vs. contiguity) as the other. In terms of reading accuracy, the participants had significantly higher accuracy scores on phonologically regular pseudowords (single mode, 84.43%; contiguity mode, 83.42%) than on irregular words (single mode, 77.64%; contiguity mode, 78.99%) [$F(1,78) = 22.69$, $p < .0001$]. However, there was no accuracy difference between presenting the words singly or in contiguity [$F(1,78) = 0.29$, $p > .05$]. There also was no significant word type × presentation mode interaction [$F(1,78) = 2.44$, $p > .05$]. In terms of reading latency, the participants had significantly longer naming latency for pseudowords (single mode, 957.44 msec; contiguity mode, 925.63 msec) than for irregular words (single mode, 901.15 msec; contiguity mode, 871.21 msec) [$F(1,78) = 8.17$, $p = .0055$]. There was no difference between presenting the words singly or in contiguity [$F(1,78) = 3.38$, $p > .05$]. There was also no significant word type × presentation mode interaction [$F(1,78) = 0.05$, $p > .05$].

Pearson correlation coefficients among the visual, auditory, and reading measures are listed in Appendix B. Only some special aspects of the correlation will be stressed below.

FSEN2 correlated significantly with the auditory gap detection measures AGAP15 ($r = .3843$) and AGAP100 ($r = .2965$) and also with reading accuracies ISA ($r = -.4163$), PSA ($r = -.3109$), and PCA ($r = -.4566$). On the other hand, FSEN12 correlated significantly with ISA ($r = -.3023$). This implies that the more sensitive a visual system is at detecting low and high temporal frequency, the better the reading accuracy is. Moreover, better visual resolution is associated with better auditory resolution. The result is suggestive of a transmodal mechanism across vision and audition.

The visual TOJ measures also correlated significantly with the auditory measures and IQ. VTOJ1 correlated with AGAP15 ($r = .2261$), AGAP100 ($r = .312$), ATOJ15 ($r = .287$), ATOJ75 ($r = .41$), ATOJ200 ($r = .345$), and IQ ($r = -.2266$). VTOJ7 correlated with AGAP15 ($r = .2463$), ATOJ15 ($r = .2842$), ATOJ75 ($r = .2731$), ATOJ200 ($r = .3762$), IQ ($r = -.2845$), and PSA ($r = -.2418$). This implies that the more sensitive a visual system is at detecting low and high spatial frequency, the better the auditory temporal resolution, reading accuracy, and IQ are.

Visible persistence measures correlated significantly with auditory gap detection, irregular word reading accuracy, and IQ. BLAN12 correlated with AGAP15 ($r = .2871$) and AGAP100 ($r = .254$). FLICK2 correlated with ISA ($r = -.2722$), ICA ($r = -.266$), and IQ ($r = -.2795$). FLICK12 correlated with ISA ($r = -.2911$) and IQ ($r = -.2213$). This implies that poorer high spatial frequency gap detection is related to poorer AGAP. Also, a stronger visual system in detecting flicker is associated with better accuracy when irregular words are read.

Flicker fusion significantly correlated with ATOJ. CHAS2 correlated with ATOJ75 ($r = .2451$) and ATOJ200 ($r = .2536$). This indicates that poorer low spatial frequency flicker fusion is related to longer auditory SOAs at long stimulus durations.

AGAP correlated significantly with pseudoword reading accuracy and IQ. AGAP15 correlated with PSA ($r = -.3796$), PCA ($r = -.3883$), and IQ ($r = -.3427$). This indicates that better AGAP is related to higher pseudoword reading accuracy and IQ.

ATOJ correlated significantly with pseudoword reading accuracy and IQ. ATOJ15 correlated with PCA ($r = -.2406$) and IQ ($r = -.2566$). ATOJ75 correlated with PSA ($r = -.2421$), PCA ($r = -.2724$), and IQ ($r = -.2978$). ATOJ200 correlated with PCA ($r = -.283$) and IQ ($r = -.3036$). This implies that shorter auditory SOAs are related to better pseudoword reading accuracy and IQ.

IQ significantly correlated with reading accuracy: ISA ($r = .2621$), ICA ($r = .454$), PSA ($r = .2547$), and PCA ($r = .2678$). This indicates that the higher the IQ, the better the reading accuracy.

To further elucidate the relationship between the temporal and the reading measures, partial correlation coefficients among the visual, auditory, and reading measures, controlling for IQ, were computed in Appendix C.

The pattern of correlation was similar to that of the Pearson correlation, even when IQ was controlled for. FSEN2 significantly correlated with AGAP15 ($r = .351$), AGAP100 ($r = .284$), ISA ($r = -.395$), PSA ($r = -.28$), and PCA ($r = -.432$). FSEN12 correlated significantly with ISA ($r = -.284$). Therefore, better visual temporal resolution is associated with better auditory temporal resolution and reading accuracy.

VTOJ1 correlated significantly with AGAP100 ($r = .297$), ATOJ15 ($r = .243$), ATOJ75 ($r = .368$), and ATOJ200 ($r = .298$). VTOJ7 correlated significantly with ATOJ15 ($r = .228$) and ATOJ200 ($r = .317$). This implies a transmodal temporal processing mechanism across vision and audition.

BLAN2 correlated significantly with AGAP15 ($r = .229$). BLAN12 correlated with AGAP15 ($r = .247$) and AGAP100 ($r = .241$). FLICK12 correlated with ISA ($r = -.248$). This implies that a high visual gap detection threshold is related to poorer AGAP and lower accuracy when irregular words are read.

AGAP15 correlated significantly with PSA ($r = -.322$) and PCA ($r = -.328$). This indicates that shorter AGAP is related to higher pseudoword reading accuracies.

In sum, both the Pearson and the partial correlations showed that better visual temporal resolution was related to better auditory temporal resolution. Moreover, higher IQ was associated with better temporal resolution and reading performance. There were more significant correlations between the visual measures and the irregular word reading accuracies and between the auditory measures and the pseudoword reading accuracies.

Stepwise multiple regressions were run on the IS, IC, PS, and PC data, individually, to determine the relative contribution of the visual, auditory, and IQ measures to word recognition in each condition. In one equation, the predictors of the model were the temporal-processing measures and IQ, and the dependent variable was reading accuracy. In another equation, the same predictors were used, but the dependent variable was the latency. An outlier was identified and discarded if the absolute value of its standardized residual was greater than 3.

Regressions run on the reading latency yielded nonsignificant results. Significant results were obtained for reading accuracy.

Stepwise Regression on Irregular Word Single Mode Accuracy

One outlier (Participant 64) was identified and discarded. The model significantly accounted for 25.8% of the variance explained in ISA [$F(2,75) = 13.06, p < .05$]. FSEN2 (a low temporal frequency measure) was the first variable that entered into the regression equation and accounted for 18.5% of the variance explained. IQ was the second variable that entered into the equation and accounted for an extra 7.3% of the explained variance.

Stepwise Regression on Irregular Word Contiguity Mode Accuracy

The model significantly accounted for 20.6% of the variance explained in ICA [$F(1,77) = 19.99, p < .05$]. IQ was the only variable that entered into the regression equation.

Stepwise Regression on Phonologically Regular Pseudoword Single Mode Accuracy

One outlier (Participant 26) was identified and discarded. AGAP15 was the first variable that entered into the regression equation and accounted for 16% of the explained variance [$F(1,76) = 14.43, p < .05$]. No other variable added a significant amount of variance in the analysis.

Stepwise Regression on Phonologically Regular Pseudoword Contiguity Mode Accuracy

The model significantly accounted for 26.2% of the variance explained in PCA [$F(2,76) = 13.46, p < .05$]. FSEN2 was the first variable that entered into the regression equation and accounted for 20.8% of the variance explained. AGAP15 added another 5.4% to the explained variance.

When stepwise regression was run on the combined speed–accuracy score (sum of reading latency and accuracy), nonsignificant results were obtained in the single and contiguity mode of irregular words and in the single mode of pseudowords. For pseudowords presented in contiguity, BLAN2 (visible persistence at 2 c/d) significantly predicted 5.5% of the explained variance in the combined score [$F(1,77) = 4.49$, $p < .05$]. BLAN12 (visible persistence at 12 c/d) accounted for an extra 6.2% of the explained variance [$F(2,76) = 5.03$, $p < .05$], followed by AGAP15, which added another 5.5% to the explained variance [$F(3,75) = 5.19$, $p < .05$].

In sum, auditory gap detection at 15 msec predicted pseudoword reading in both single and contiguity mode accuracies. There was some visual (FSEN2) involvement in the accuracies of isolated irregular words and pseudowords presented in contiguity. IQ also played a role in irregular word accuracies. When a combined speed–accuracy score was computed, both the low (BLAN2) and the high (BLAN12) spatial frequency visual measures and AGAP were involved in reading pseudowords presented in contiguity.

DISCUSSION

The correlation analyses suggested a generalized timing mechanism in the processing of rapidly presented information (Miller & Tallal, 1995) because better visual temporal resolution was related to better auditory temporal resolution. Higher IQ was associated with better temporal resolution and reading performance. This is consistent with Raz, Willerman, and Yama (1987), Olson and Datta (2002), and Rosen (2003). IQ, particularly performance IQ, accounts for the ability to process rapidly presented visual and auditory stimuli, as well as reading (Baddeley & Gathercole, 1992) and naming (McGeorge, Crawford, & Kelly, 1996) speed. More specifically, IQ predicted the accuracies of irregular words presented both singly and in contiguity. In the reading of irregular words, good sight word skills and spatial analysis are needed. The requirement of spatial analysis may have highlighted the role of IQ in this reading condition. Moreover, we used Raven's (1962), which is strongly related to spatial processing and performance IQ. It may have tapped into the spatial analysis in word reading more closely and, hence, augmented the significance of IQ in the reading of irregular words.

Interestingly, the multiple regressions almost produced a single sensory task as the correlate with each reading task. It suggested considerable overlap among the sensory tasks with one that tended to stand out over the others. If we took a closer look at the sensory tasks and the perceptual demands each made, all the visual and auditory tasks required the processing of a temporal gap in between or within the stimuli. This might have mediated a moderate correlation among the tasks and, hence, a situation similar to that of multicolinearity (Tabachnick & Fidell, 2001). Hence, one temporal task stood out over the others. As a matter of fact, poor readers have difficulties detecting the temporal gap between pairs of stimuli presented visually, auditorily, cross-modally (Laasonen et al., 2002; Meyler & Breznitz, 2005), and intramodally (Rose et al., 1999). It seems that cross-modal and intramodal gap detection of rapidly presented stimuli constitutes a generalized timing mechanism.

More significant correlations were found between the visual and the irregular word measures and between the auditory and the pseudoword measures. The results are consistent with the notion that dyslexic subtypes have selective temporal deficits in different modalities (Booth et al., 2000; Farmer & Klein, 1995; Talcott et al., 2000). Moreover, the findings echoed Talcott et al. (2003), so that visual temporal sensitivity is more apparent in languages with irregular orthographies. Stein (2003) and Stein and Talcott (1999) argued that visual processes are important to the development of orthographic skills. Accurate visual coding is needed to identify a word in terms of its letter positions. The graphemes and phonemes are then identified to retrieve the pronunciation. Similarly, Wolf and Bowers (1999) conceived that better visual temporal ability is related to effective processing of visual letter configuration, leading to faster naming speed and, hence, better orthographic skills. Since temporal differences are more pronounced in languages with orthographic irregularities (Talcott et al., 2003), irregular words or logographic languages such as Chinese would be a sensitive media for testing the temporal deficit hypothesis, particularly in the visual domain.

In harmony with the notion that rapid auditory temporal acuity and phonological processes are closely related (Laasonen et al., 2002), the regression analyses showed that the auditory temporal-processing measures predicted pseudoword reading in both the single and the contiguity mode. Phonologically regular pseudowords were read more slowly but also more accurately than the irregular words in our study. Although the increased time of pseudoword viewing might have increased the likelihood of correct responses, the findings are consistent with the fact that the grapheme–phoneme conversion route is analytical and, therefore, is slower than the visual route in reading (Coltheart, 1978). However, the results were inconsistent with Ahissar et al. (2000), who showed that adults with a childhood history of reading difficulty were not impaired in detecting an energy gap of two 500-msec noise bursts. It is possible that gap detection is relevant to language processing only if the stimulus has a very short duration, like 15 msec in our study. We did not use tones in auditory gap detection, as compared with previous studies (e.g., Reed, 1989; Tallal, 1980), because we wanted to examine participants' performance on nonspeech stimuli, as opposed to tones, which may share more characteristics with speech stimuli in frequency and pitch dimension. This study showed that rapid auditory nonspeech stimuli can have an impact on reading processes.

Although this experiment did not use dyslexic participants, normal reading adults seem to use their visual and auditory temporal processes the same way as poor readers do in reading irregular words and pseudowords presented singly and in contiguity. To illustrate, normal reading adults, like disabled readers, rely more on auditory functions to process pseudowords and on visual processes to read irregular words. This further illustrates that reading disability may not be so distinct from normal reading with respect to some reading and cognitive processes (Au & Lovegrove, 2001a, 2001b). Sensory processing skills in both visual and auditory modalities accounted for a good deal of variance in the reading performance of normal undergraduates, not just in that of reading-impaired students.

Our results showed that a low temporal frequency visual measure was involved in the accuracies of isolated irregular words and pseudowords presented in contiguity. When a combined speed–accuracy score was used, both the low (BLAN2) and the high (BLAN12) spatial frequency visual measures were active in reading pseudowords presented in contiguity.

It was once hypothesized that the magnocellular visual pathway responsible for temporal processing flushed the iconic memory to prevent blur from superimposed retinal signals. Breitmeyer (1980) proposed that the magnocellular visual pathway suppressed the parvocellular visual pathway during a saccade to prevent blur between two retinal images, supposing that all text processing was done by the parvocellular pathway and none by the magnocellular pathway. However, recent studies have shown that it is the parvocellular visual pathway suppressing the magnocellular visual pathway (Irwin & Brockmole, 2004), and not the other way around. Thus, the role of the magnocellular visual pathway in reading has changed and the model has been abandoned (Breitmeyer & Ogmen, 2000). Consequently, alternative explanations concerning the role of the magnocellular visual pathway in reading have been presented. These include letter position encoding (Cornelissen & Hansen, 1998), whole-word pattern recognition, processing of the low spatial frequency components of text (Chase et al., 2003), and visual attention (Pammer et al., 2004). The findings are, in particular, consistent with those in Cornelissen and Hansen (1998), because the low temporal frequency variable was active in the reading of both single irregular words and pseudowords presented in contiguity. Hence, visual temporal function is related to letter-by-letter reading, which is relevant to both irregular word and pseudoword reading. Rapid visual processing, via the perception of letter and word order, provides a gateway by which textual information enters the brain.

In this study, only a low temporal, but not a high temporal, frequency visual measure actively processed the accuracies of isolated irregular words and pseudowords presented in contiguity. Both the low (BLAN2) and the high (BLAN12) spatial frequency visual measures were involved in the reading of pseudowords presented in contiguity when the combined speed–accuracy score was taken into account. In general, spatial frequencies of 7 c/d or above are adequate to isolate nontemporal visual processes, whereas a temporal frequency of 12 Hz is good enough to segregate the visual temporal processes. Thus, we expected high temporal/low spatial frequency variables to tap more closely into the temporal processes than would the low temporal/high spatial frequency variables (Burr et al., 1994; Livingstone & Hubel, 1988). The results are puzzling given that the high temporal/low spatial frequency measures that tap more closely into the temporal processes seemed to be less involved than their low temporal/high spatial frequency counterparts in predicting reading performance. As was mentioned before, correlations among various temporal tasks may have made one visual task stand out over the other visual tasks. Furthermore, the results provide some support that saccades induce parvo suppression of magno function, and not the other way around, as was suggested by Breitmeyer (1980).

Tasks that operate under isoluminant color or photopic conditions (Chase et al., 2003; Cornelissen et al., 1995; Livingstone & Hubel, 1987, 1988) are more sensitive to nontemporal visual processes. On the other hand, motion stimuli (Conlon et al., 2004; Scheuerpflug et al., 2004) and frequency doubling (Pammer et al., 2004) are more likely to tap into the temporal processes. Since these tasks were not available at time of testing, we were not able to run these tests. Comparing these tests with respect to the reading of irregular words and pseudowords presented singly and in contiguity may make the selective involvement of various visual processes more obvious in different word presentation formats.

Mitchell and Neville (2004) showed that the dorsal visual stream—the "where" pathway that is responsible for the processing of temporal stimuli—is more plastic than is the ventral stream, in that it takes a longer developmental time course across the early school years. Since the development of temporal sensitivity is more dynamic at a young age, the differential involvement of various visual processes with respect to different word presentation formats may be more apparent in children (Pammer et al., 2004) than in adults.

In the contiguity mode of presentation, the "+" guided the spatial separation between words. The participants were told not to move their eyes to the next cross until the word under that cross appeared. Although no eye movements were recorded, the aim of the instructions was to avoid the participants' making preemptory eye movements. The unnatural reading situation was far from true continuous text reading because the saccades were cued and no peripheral word-level information was given. Chase et al. (2003) argued that visual temporal processes are required to process the low spatial frequency components of text. Such criteria are more likely to be found in a natural reading situation, such as the reading of whole text that provides peripheral information (e.g., Chase et al., 2003; Pammer et al., 2004). Given the lack of peripheral information, our reading condition may not have fully captured the function of the visual temporal processes. Accordingly, the selective involvement of the visual processes with respect to various word presentation formats was less prominent in our study.

Undergraduates were recruited as participants in this study. The mean of their IQ was 110, which is above average among the general population. In addition, they were proficient readers who would have developed more sophisticated skills and strategies to attempt various reading tasks. The above-average cognitive ability may have overtaken or masked the contribution of the temporal processes in word reading. Moreover, we were concerned about whether there was sufficient reading performance variability among these undergraduates, particularly since accuracy was the only useful dependent measure. In general, children produce more positive findings than do adults regarding differences in temporal processing (Pammer et al., 2004). Nevertheless, the results of the multiple regressions suggested that these sensory measures were predictive of reading despite the limited reading performance variability of normal adults. Including a wider range of normally reading adults and children may produce a clearer picture of how temporal processes are related to different types of word presentation.

In sum, rapid visual processes are related to the reading of irregular words, whereas rapid auditory processes are related to the reading of pseudowords. The findings illustrate the relevance of orthographic irregularity in testing the visual measures. The low temporal frequency visual measure was active in processing single irregular words and pseudowords presented in contiguity. Both the low and the high spatial frequency visible persistence measures were active in processing the combined speed–accuracy scores of pseudowords presented in contiguity. The differential involvement of the visual processes in the processing of words presented singly and in contiguity should be more evident when isoluminant tasks and motion stimuli are used in testing the visual processes and when a word presentation format that provides peripheral information (e.g., whole text) is adopted. Temporal acuity remains important to reading even in normal, adult readers. The results were suggestive of a generalized timing mechanism that is closely related to IQ.

AUTHOR NOTE

Correspondence concerning this article should be addressed to A. Au, Department of Psychology, Faculty of Arts and Social Sciences, James Cook University, P.O. Box 6811, Cairns QLD 4870, Australia (e-mail: agnes.au@jcu.edu.au).

REFERENCES

Ahissar, M., Protopapas, A., Reid, M., & Merzenich, M. M. (2000). Auditory processing parallels reading abilities in adults. *Proceedings of the National Academy of Sciences*, **97**, 6832-6837.

Au, A., & Lovegrove, B. (2001a). The role of visual and auditory temporal processing in reading irregular and nonsense words. *Perception*, **30**, 1127-1142.

Au, A., & Lovegrove, B. (2001b). Temporal processing ability in above average and average readers. *Perception & Psychophysics*, **63**, 148-155.

Baayen, R. H., Piepenbrock, R., & Gulikers, L. (1995). The CELEX Lexical Database (Release 2) [CD-ROM]. Philadelphia, PA: Linguistic Data Consortium, University of Pennsylvania [Distributor].

Baddeley, A., & Gathercole, S. (1992). Learning to read: The role of the phonological loop. In J. Alegría, D. Holender, J. Junca de Morais, & M. Radeau (Eds.), *Analytic approaches to human cognition* (pp. 153-167). Amsterdam: North-Holland.

Becker, C., Elliott, M. A., & Lachman, T. (2005). Evidence for impaired visuoperceptual organization in developmental dyslexics and its relation to temporal processes. *Cognitive Neuropsychology*, **22**, 499-522.

Benasich, A. A., & Tallal, P. (1996). Auditory temporal processing thresholds, habituation, and recognition memory over the 1st year. *Infant Behavior & Development*, **19**, 339-357.

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

Ben-Yehudah, G., Banai, K., & Ahissar, M. (2004). Patterns of deficit in auditory temporal processing among dyslexic adults. *NeuroReport*, **15**, 627-631.

Boden, C., & Brodeur, D. A. (1999). Visual processing of verbal and nonverbal stimuli in adolescents with reading disabilities. *Journal of Learning Disabilities*, **32**, 58-71.

Booth, J. R., Perfetti, C. A., MacWhinney, B., & Hunt, S. B. (2000). The association of rapid temporal perception with orthographic and phonological processing in children and adults with reading impairment. *Scientific Studies of Reading*, **4**, 101-132.

Bourne, L. E., Young, S. R., & Angell, L. S. (1986). Resource allocation in reading: An interactive approach. *Zeitschrift für Psychologie*, **194**, 155-176.

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

Breitmeyer, B. G. (1980). Unmasking visual masking: A look at the “why” behind the veil of the “how.” *Psychological Review*, **87**, 52-69.

Breitmeyer, B. G., & Ogmen, H. (2000). Recent models and findings in visual backward masking: A comparison, review, and update. *Perception & Psychophysics*, **62**, 1572-1595.

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.

Burr, D. C., Morrone, M. C., & Ross, J. (1994). Selective suppression of the magnocellular visual pathway during saccadic eye movements. *Nature*, **371**, 511-513.

Cacace, A. T., McFarland, D. J., Ouimet, J. R., Schrieber, E. J., & Marro, P. (2000). Temporal processing deficits in remediation-resistant reading-impaired children. *Audiology & Neuro-Otology*, **5**, 83-97.

Castles, A., & Coltheart, M. (1993). Varieties of developmental dyslexia. *Cognition*, **47**, 149-180.

Chase, C., Ashourzadeh, A., Kelly, C., Monfette, S., & Kinsey, K. (2003). Can the magnocellular pathway read? Evidence from studies of color. *Vision Research*, **43**, 1211-1222.

Chase, C., & Jenner, A. R. (1993). Magnocellular visual deficits affect temporal processing of dyslexics. In P. Tallal, A. M. Galaburda, R. R. Llinás, & C. von Euler (Eds.), *Temporal information processing in the nervous system: Special reference to dyslexia and dysphasia* (Annals of the New York Academy of Sciences, Vol. 682, pp. 326-329). New York: New York Academy of Sciences.

Chiappe, P., Stringer, R., Siegel, L. S., & Stanovich, K. E. (2002). Why the timing deficit hypothesis does not explain reading disability in adults. *Reading & Writing*, **15**, 73-107.

Coltheart, M. (1978). Lexical access in simple reading tasks. In G. Underwood (Ed.), *Strategies of information processing* (pp. 151-216). San Diego: Academic Press.

Coltheart, M., Rastle, K., Perry, C., Langdon, R., & Ziegler, J. (2001). DRC: A dual route cascaded model of visual word recognition and reading aloud. *Psychological Review*, **108**, 204-256.

Conlon, E., Sanders, M., & Zapart, S. (2004). Temporal processing in poor adult readers. *Neuropsychologia*, **42**, 142-157.

Cornelissen, P. L., & Hansen, P. C. (1998). Motion detection, letter position encoding, and single word reading. *Annals of Dyslexia*, **48**, 155-188.

Cornelissen, P. [L.], Richardson, A., Mason, A., Fowler, S., & Stein, J. (1995). Contrast sensitivity and coherent motion detection measured at photopic luminance levels in dyslexics and controls. *Vision Research*, **35**, 1483-1495.

Demb, J. B., Boynton, G. M., Best, M., & Heeger, D. J. (1997). Psychophysical evidence for a magnocellular pathway deficit in dyslexia. *Vision Research*, **38**, 1555-1559.

Denenberg, V. H. (1999). A critique of Mody, Studdert-Kennedy, and Brady’s “Speech perception deficits in poor readers: Auditory processing or phonological coding?” *Journal of Learning Disabilities*, **32**, 379-383.

Edwards, V. T., Giaschi, D. E., Dougherty, R. F., Edgell, D., Bjornson, B. H., Lyons, C., & Douglas, R. M. (2004). Psychophysical indexes of temporal processing abnormalities in children with developmental dyslexia. *Developmental Neuropsychology*, **25**, 321-354.

Facoetti, A., & Lorusso, M. L. (2000). Different approaches in the study of developmental dyslexia. *Saggi: Child Development & Disabilities*, **26**, 65-71.

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

France, S. J., Rosner, B. S., Hansen, P. C., Calvin, C., Talcott, J. B., Richardson, A. J., & Stein, J. F. (2002). Auditory frequency discrimination in adult developmental dyslexics. *Perception & Psychophysics*, **64**, 169-179.

GALABURDA, A. M., & LIVINGSTONE, M. [S.] (1993). Evidence for a magnocellular defect in developmental dyslexia. In P. Tallal, A. M. Galaburda, R. R. Llinás, & C. von Euler (Eds.), *Temporal information processing in the nervous system: Special reference to dyslexia and dysphasia* (Annals of the New York Academy of Sciences, Vol. 682, pp. 70-82). New York: New York Academy of Sciences.

GROSS-GLENN, K., SKOTTUN, B. C., GLENN, W., KUSHCH, A., LINGUA, R., DUNBAR, M., ET AL. (1995). Contrast sensitivity in dyslexia. *Visual Neuroscience*, **12**, 153-163.

HARI, R., & KIESILÄ, P. (1996). Deficit of temporal auditory processing in dyslexic adults. *Neuroscience Letters*, **205**, 138-140.

HAUTUS, M. J., SETCHELL, G. J., WALDIE, K. E., & KIRK, I. J. (2003). Age-related improvements in auditory temporal resolution in reading-impaired children. *Dyslexia*, **9**, 37-45.

HEATH, S. M., HOGBEN, J. H., & CLARK, C. D. (1999). Auditory temporal processing in disabled readers with and without oral language delay. *Journal of Child Psychology & Psychiatry & Allied Disciplines*, **40**, 637-647.

HEIERVANG, E., STEVENSON, J., & HUGDAHL, K. (2002). Auditory processing in children with dyslexia. *Journal of Child Psychology & Psychiatry & Allied Disciplines*, **43**, 931-938.

HILL, R., & LOVEGROVE, W. J. (1993). One word at a time: A solution to the visual deficit in the Specific Reading Disabled? In S. F. Wright & R. Groner (Eds.), *Facets of dyslexia and its remediation* (pp. 65-76). Amsterdam: Elsevier, North-Holland.

HOOD, M., & CONLON, E. (2004). Visual and auditory temporal processing and early reading development. *Dyslexia*, **10**, 234-252.

IRWIN, D. E., & BROCKMOLE, J. R. (2004). Suppressing where but not what: The effect of saccades on dorsal- and ventral-stream visual processing. *Psychological Science*, **15**, 467-473.

JUOLA, J. F., TIRITOĞLU, A., & PLEUNIS, J. (1995). Reading text presented on a small display. *Applied Ergonomics*, **26**, 227-229.

KELLY, J. B., ROONEY, B. J., & PHILLIPS, D. P. (1996). Effects of bilateral auditory cortical lesions on gap-detection thresholds in the ferret (*Mustela putorius*). *Behavioral Neuroscience*, **110**, 542-550.

KRAUS, N., MCGEE, T. J., CARRELL, T. D., ZECKER, S. G., NICOL, T. G., & KOCH, D. B. (1996). Auditory neurophysiologic responses and discrimination deficits in children with learning problems. *Science*, **273**, 971-973.

LAASONEN, M., SERVICE, E., & VIRSU, V. (2002). Crossmodal temporal order and processing acuity in developmentally dyslexic young adults. *Brain & Language*, **80**, 340-354.

LIVINGSTONE, M. S., & HUBEL, D. H. (1987). Psychophysical evidence for separate channels for the perception of form, color, movement, and depth. *Journal of Neuroscience*, **7**, 3416-3468.

LIVINGSTONE, M. [S.], & HUBEL, D. [H.] (1988). Segregation of form, color, movement, and depth: Anatomy, physiology, and perception. *Science*, **240**, 740-749.

LOVEGROVE, W., HEDDLE, M., & SLAGHUIS, W. (1980). Reading disability: Spatial frequency specific deficits in visual information store. *Neuropsychologia*, **18**, 111-115.

LYYTINEN, H., GUTTORM, T. K., HUTTUNEN, T., HÄMÄLÄINEN, J., LEPPÄNEN, P. H. T., & VESTERINEN, M. (2005). Psychophysiology of developmental dyslexia: A review of findings including studies of children at risk for dyslexia. *Journal of Neurolinguistics*, **18**, 167-195.

MARTOS, F. J., & MARMOLEJO, A. (1993). Visible persistence in developmental dyslexia. In P. Tallal, A. M. Galaburda, R. R. Llinás, & C. von Euler (Eds.), *Temporal information processing in the nervous system: Special reference to dyslexia and dysphasia* (Annals of the New York Academy of Sciences, Vol. 682, pp. 383-386). New York: New York Academy of Sciences.

MAY, J. G., WILLIAMS, M. C., & DUNLAP, W. P. (1988). Temporal order judgments in good and poor readers. *Neuropsychologia*, **26**, 917-924.

MCANALLY, K. I., CASTLES A., & BANNISTER, S. (2004). Auditory temporal pattern discrimination and reading ability. *Journal of Speech, Language, & Hearing Research*, **47**, 1237-1243,

MCANALLY, K. I., & STEIN, J. F. (1996). Auditory temporal coding in dyslexia. *Proceedings of the Royal Society of London: Series B*, **263**, 961-965.

MCARTHUR, G. M., & BISHOP, D. V. M. (2001). Auditory perceptual processing in people with reading and oral language impairments: Current issues and recommendations. *Dyslexia*, **7**, 150-170.

MCCROSKEY, R. L., & KIDDER, H. C. (1980). Auditory fusion among learning disabled, reading disabled, and normal children. *Journal of Learning Disabilities*, **13**, 69-76.

MCGEORGE, P., CRAWFORD, J. R., & KELLY, S. W. (1996). The relationship between WAIS–R abilities and speed of processing in a word identification task. *Intelligence*, **23**, 175-190.

MEYLER A., & BREZNITZ, Z. (2005). Visual, auditory and cross-modal processing of linguistic and nonlinguistic temporal patterns among adult dyslexic readers. *Dyslexia*, **11**, 93-115.

MILLER, S. L., & TALLAL, P. (1995). A behavioral neuroscience approach to developmental language disorders: Evidence for a rapid temporal processing deficit. In D. Cicchetti, & D. J. Cohen (Eds.), *Developmental psychopathology: Vol 2. Risk, disorder, and adaptation* (pp. 274-298). New York: Wiley.

MITCHELL, T. V., & NEVILLE, H. J. (2004). Asynchronies in the development of electrophysiological responses to motion and color. *Journal of Cognitive Neuroscience*, **16**, 1363-1374.

MODY, M., STUDDERT-KENNEDY, M., & BRADY, S. (1997). Speech perception deficits in poor readers: Auditory processing or phonological coding? *Journal of Experimental Child Psychology*, **64**, 199-231.

NELSON, H. E. (1982). *National Adult Reading Test (NART)*. Windsor: NFER-Nelson.

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

OLSON, R., & DATTA, H. (2002). Visual temporal processing in reading-disabled and normal twins. *Reading & Writing*, **15**, 127-149.

PAMMER, K., LAVIS, R., & CORNELISSEN, P. (2004). Visual encoding mechanisms and their relationship to text presentation preference. *Dyslexia*, **10**, 77-94.

PHILLIPS, D. P., & FARMER, M. E. (1990). Acquired word deafness, and the temporal grain of sound representation in the primary auditory cortex. *Behavioral Brain Research*, **40**, 85-94.

RAMUS, F. (2004). Neurobiology of dyslexia: A reinterpretation of the data. *Trends in Neurosciences*, **27**, 720-726.

RAVEN, J. C. (1962). *Advanced Raven's Progressive Matrices*. Melbourne: Australian Council for Educational Research.

RAZ, N., WILLERMAN, L., & YAMA, M. (1987). On sense and senses: Intelligence and auditory information processing. *Personality & Individual Differences*, **8**, 201-210.

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

ROSE, S. A., FELDMAN, J. F., JANKOWSKI, J. J., & FUTTERWEIT, L. R. (1999). Visual and auditory temporal processing, cross-modal transfer, and reading. *Journal of Learning Disabilities*, **32**, 256-266.

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.

SCHEUERPFLUG, P., PLUME, E., VETTER, V., SCHULTE-KÖRNE, G., DEIMEL, W., BARTLING, J., ET AL. (2004). Visual information processing in dyslexic children. *Clinical Neurophysiology*, **115**, 90-96.

SCHULTE-KÖRNE, G., DEIMEL, W., BARTLING, J., & REMSCHMIDT, H. (1999). The role of phonological awareness, speech perception, and auditory temporal processing for dyslexia. *European Child & Adolescent Psychiatry*, **8**(Suppl. 3), III/28-III/34.

SCHULTE-KÖRNE, G., DEIMEL, W., BARTLING, J., & REMSCHMIDT, H. (2004). Motion-onset VEPs in dyslexia: Evidence for visual perceptual deficit. *NeuroReport*, **15**, 1075-1078.

SHAPIRO, K. L., OGDEN, N., & LIND-BLAD, F. (1990). Temporal processing in dyslexia. *Journal of Learning Disabilities*, **23**, 99-107.

SHARE, D. L., JORM, A. F., MACLEAN, R., & MATTHEWS, R. (2002). Temporal processing and reading disability. *Reading & Writing*, **15**, 151-178.

SLAGHUIS, W. L., & LOVEGROVE, W. J. (1985). Spatial-frequency-dependent visible persistence and specific reading disability. *Brain & Cognition*, **4**, 219-240.

SOLAN, H. A. (2004). Visual and auditory processing in reading disability: A matter of cognitive dissonance. *Journal of Optometric Vision Development*, **35**, 16-21.

SOLAN, H. A., HANSEN, P. C., SHELLEY-TREMBLAY, J., & FICARRA, A. (2003). Coherent motion threshold measurements for M-cell deficit differ for above- and below-average readers. *Optometry*, **74**, 727-734.

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

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

Studdert-Kennedy, M. (2002). Deficits in phoneme awareness do not arise from failures in rapid auditory processing. *Reading & Writing*, **15**, 5-14.

Studdert-Kennedy, M., & Mody, M. (1995). Auditory temporal perception deficits in the reading-impaired: A critical review of the evidence. *Psychonomic Bulletin & Review*, **2,** 508-514.

Studdert-Kennedy, M., Mody, M., & Brady, S. (2000). Speech perception deficits in poor readers: A reply to Denenberg's critique. *Journal of Learning Disabilities*, **33**, 317-321.

Tabachnick, B. G., & Fidell, L. S. (2001). *Using multivariate statistics* (4th ed.). Boston: Allyn & Bacon.

Talcott, J. B., Gram, A., Van Ingelghem, M., Witton, C., Stein, J. F., & Toennessen, F. E. (2003). Impaired sensitivity to dynamic stimuli in poor readers of a regular orthography. *Brain & 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.

Talcott, T. B., Witton, C., McLean, M. F., Hansen, P. C., Rees, A., Green, G. G. R., & Stein, J. (2000). Dynamic sensory sensitivity and children's word decoding skills. *Proceedings of the National Academy of Sciences*, **97**, 2952-2957.

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

Tallal, P. (2003). Language learning disabilities: Integrating research approaches. *Current Directions in Psychological Science*, **12**, 206-211.

Tallal, P., Stark, R. E., & Mellits, D. (1985). Identification of language-impaired children on the basis of rapid perception and production skills. *Brain & Language*, **25**, 314-322.

Trehub, S. E., & Henderson, J. L. (1996). Temporal resolution in infancy and subsequent language development. *Journal of Speech & Hearing Research*, **39**, 1315-1320.

Walker, M. M., Shinn, J. B., Cranford, J. L., Givens, G. D., & Holbert, D. (2002). Auditory temporal processing performance of young adults with reading disorders. *Journal of Speech, Language, & Hearing Research*, **45**, 598-605.

Wetherill, G. B., & Levitt, H. (1965). Sequential estimation of points on a psychometric function. *British Journal of Mathematical & Statistical Psychology*, **18**, 1-10.

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. (2004). Two visual motion processing deficits in developmental dyslexia associated with different reading skills deficits. *Journal of Cognitive Neuroscience*, **16**, 528-540.

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.

Wolf, M., & Bowers, P. G. (1999). The double-deficit hypothesis for the developmental dyslexias. *Journal of Educational Psychology*, **91**, 415-438.

Woodcock, R. W. (1984). *Woodcock Language Proficiency Battery*. Allen, TX: DLM Teaching Resources.

Woodcock, R. W. (1987). *Woodcock Reading Mastery Tests–Revised*. Circle Pines, MN: American Guidance Service.

APPENDIX A

Irregular Word and Phonologically Regular Pseudoword Reading Task

	Irregular Word		Phonologically Regular Pseudoword			Irregular Word		Phonologically Regular Pseudoword	
Item	List 1	List 2	List 1	List 2	Item	List 1	List 2	List 1	List 2
1	come	sure	gop	teg	16	chord	ache	rayed	coge
2	shoe	lose	nad	lif	17	aisle	depot	squow	byrcal
3	pint	choir	sut	thim	18	deny	psalm	mieb	phigh
4	tomb	cough	phot	chut	19	nausea	debt	hudned	quog
5	soul	iron	sith	giph	20	rarefy	naive	lindify	pnir
6	wolf	bowl	hoil	toud	21	gaoled	thyme	cythe	throbe
7	blood	quay	gead	daul	22	heir	hiatus	nolhod	sloy
8	gauge	break	prin	stet	23	gist	subtle	cedge	depine
9	island	answer	mulp	roin	24	simile	banal	whumb	lunap
10	ceiling	pretty	nint	gren	25	facade	cellist	knoink	dinlan
11	debris	indict	gurdet	torlep	26	drachm	zealot	expram	rhunk
12	regime	meringue	tadlen	latsar	27	aeon	idyll	dreek	imbaf
13	bouquet	beret	polmex	tashet	28	prelate	aver	brecked	glack
14	colonel	routine	sothep	miphic	29	demesne	radix	wroutch	zoath
15	brooch	yacht	lishon	dethix	30	labile	syncope	rejune	pertome

Note—Items 1–15 of both the irregular words and the phonologically regular pseudowords were taken from Castles and Coltheart (1993). Items 16–30 of the irregular words were taken from the NART. Items 16–30 of the pseudowords were taken from Woodcock (1984, 1987).

(*Continued on next page*)

APPENDIX B

Correlation Matrix of the Log-Transformed Data of the Visual, Auditory, and Reading Tasks ($N = 79$)

	FSEN2	FSEN12	VTOJ1	VTOJ7	BLAN2	BLAN12	FLICK2	FLICK12	CHAS2	CHAS12	AGAP15
FSEN2	1.0000										
FSEN12	.4882**	1.0000									
VTOJ1	.0298	.1397	1.0000								
VTOJ7	.1627	.1921	.5376**	1.0000							
BLAN2	.1774	.2005	.0794	.1415	1.0000						
BLAN12	.2109	.2687*	.2047	.2585*	.6767**	1.0000					
FLICK2	.1589	.2078	.0144	.2066	.3752**	.4713**	1.0000				
FLICK12	.1087	.2346*	−.0126	.1922	.3416**	.4643**	.8134**	1.0000			
CHAS2	.1474	.0499	−.0358	.1076	.1731	.3308**	.6109**	.5612**	1.0000		
CHAS12	.1199	.0491	−.1102	.0892	.0375	.2186	.5053**	.5297**	.6837**	1.0000	
AGAP15	.3843**	.221	.2261*	.2463*	.2098	.2871*	.2488*	.143	.1877	.1613	1.0000
AGAP100	.2965**	.1705	.312**	.2051	.2007	.254*	.1702	.0658	.0881	.0839	.5715**
ATOJ15	.1849	−.001	.287*	.2842*	.045	−.0007	.1542	.0297	.1687	.0049	.2972**
ATOJ75	.1683	−.0619	.41**	.2731*	.1185	.1158	.1145	.0541	.2451*	.1646	.3917**
ATOJ200	.236*	.07	.345**	.3762**	.0148	.0409	.1541	.07	.2536*	.1477	.3193**
ISA	−.4163**	−.3023**	−.1301	−.1795	−.1559	−.1758	−.2722*	−.2911**	−.167	−.1325	−.1596
ICA	−.1169	−.1714	−.0127	−.1461	−.1349	−.1123	−.266*	−.2146	−.153	−.1164	−.0938
PSA	−.3109**	−.1157	−.1605	−.2418*	−.0806	−.0748	−.007	.1011	.0551	.0479	−.3796**
PCA	−.4566**	−.1073	−.0963	−.1335	−.0887	−.0458	−.1362	−.0981	−.0262	−.0685	−.3883**
IST	−.0456	.0503	−.044	−.0197	−.0895	.0219	−.0178	.1114	.0233	.0293	−.1021
ICT	−.0106	.0299	−.1493	−.0819	−.1497	−.0806	.086	.166	.0905	.054	−.0796
PST	−.0373	−.0042	.042	−.0084	−.0621	.1172	.051	.126	.1329	.1141	−.028
PCT	.0362	−.0467	.0353	.0125	−.2094	.0464	.0651	.1571	.1216	.0922	−.0643
IQ	−.1753	−.1165	−.2266*	−.2845**	.0158	−.1693	−.2795*	−.2213*	−.1815	−.0897	−.3427*

Note—FSEN2, FSEN12, flicker contrast sensitivity at 2 and 12 Hz, respectively; VTOJ1, VTOJ7, visual temporal order judgment at 1 and 7 c/d, respectively; BLAN2, BLAN12, visible persistence (based on the judgment of a blank) at 2 and 12 c/d, respectively; FLICK2, FLICK12, visible persistence (based on the judgment of a flicker) at 2 and 12 c/d, respectively; CHAS2, CHAS12, flicker fusion at 2 and 12 c/d, respectively; AGAP15, AGAP100, auditory gap detection at 15 and 100 msec, respectively; ATOJ15, ATOJ75, ATOJ200, auditory temporal order judgment at 15, 75, and 200 msec, respectively; ISA, ICA, irregular words accuracy, single/contiguity condition; PSA, PCA, phonologically regular pseudowords accuracy, single/contiguity condition; IST, ICT, irregular words reaction time, single/contiguity condition; PST, PCT, phonologically regular pseudowords reaction time, single/contiguity condition; IQ, nonverbal reasoning skills measured by the Advanced Raven's Progressive Matrices. $^{*}p < .05$. $^{**}p < .01$.

APPENDIX B (Continued)

AGAP100	ATOJ15	ATOJ75	ATOJ200	ISA	ICA	PSA	PCA	IST	ICT	PST	PCT	IQ
1.0000												
.1771	1.0000											
.3074**	.6756**	1.0000										
.1728	.7256**	.6488**	1.0000									
−.0346	−.0254	−.102	−.0902	1.0000								
.0491	−.1689	−.1076	−.1086	.471**	1.0000							
−.1662	−.1909	−.2421*	−.1608	.2083	.153	1.0000						
−.1827	−.2406*	−.2724*	−.283*	.4472**	.1981	.7146**	1.0000					
−.0499	.0239	.0259	−.0031	.0572	.1537	.0827	.2238*	1.0000				
−.089	−.0668	−.1607	−.03	−.0088	.0541	.0888	.0963	.7288**	1.0000			
.0006	.0422	.0292	.0964	.0901	.2196	.0087	.1315	.7139**	.5822**	1.0000		
−.0072	.034	−.0741	.0231	.0318	.124	−.127	−.0812	.6378**	.6188**	.7837**	1.0000	
−.1058	−.2566*	−.2978**	−.3036**	.2621*	.454**	.2547*	.2678*	.0384	−.0673	.0398	−.019	1.0000

APPENDIX C

Partial Correlation Matrix of the Log-Transformed Data of the Visual, Auditory, and Reading Tasks, Controlling for IQ ($N = 79$)

	FSEN2	FSEN12	VTOJ1	VTOJ7	BLAN2	BLAN12	FLICK2	FLICK12	CHAS2	CHAS12	AGAP15
FSEN2	1.000										
FSEN12	.478**	1.000									
VTOJ1	−.010	.117	1.000								
VTOJ7	.120	.167	.507**	1.000							
BLAN2	.183	.204	.085	.152	1.000						
BLAN12	.187	.254*	.173	.223*	.689**	1.000					
FLICK2	.116	.184	−.052	.138	.395**	.448**	1.000				
FLICK12	.073	.216	−.066	.138	.354**	.444**	.803**	1.000			
CHAS2	.119	.029	−.080	.059	.179	.310**	.593**	.543**	1.000		
CHAS12	.106	.039	−.135	.067	.039	.207	.502**	.525**	.681**	1.000	
AGAP15	.351**	.194	.162	.165	.229*	.247*	.170	.073	.136	.139	1.000
AGAP100	.284*	.160	.297**	.184	.204	.241*	.147	.044	.070	.075	.573**
ATOJ15	.147	−.032	.243*	.228*	.051	−.046	.089	−.029	.128	−.019	.230*
ATOJ75	.123	−.102	.368**	.206	.129	.069	.034	−.013	.204	.145	.323**
ATOJ200	.195	.037	.298**	.317**	.021	−.011	.076	.003	.212	.127	.240*
ISA	−.390**	−.284*	−.075	−.113	−.166	−.138	−.215	−.248*	−.126	−.113	−.077
ICA	−.042	−.134	.104	−.020	−.159	−.040	−.163	−.131	−.081	−.085	.074
PSA	−.280*	−.090	−.109	−.183	−.088	−.033	.069	.167	.107	.073	−.322**
PCA	−.432**	−.079	−.038	−.062	−.096	.000	−.066	−.041	.024	−.046	−.328**
IST	−.040	.055	−.036	−.009	−.090	.029	−.007	.123	.031	.033	−.095
ICT	−.023	.022	−.169	−.106	−.149	−.094	.070	.155	.080	.048	−.110
PST	−.031	.000	.052	.003	−.063	.126	.065	.138	.143	.118	−.015
PCT	.033	−.049	.032	.007	−.209	.044	.062	.157	.120	.091	−.075

Note—FSEN2, FSEN12, flicker contrast sensitivity at 2 and 12 Hz, respectively; VTOJ1, VTOJ7, visual temporal order judgment at 1 and 7 c/d, respectively; BLAN2, BLAN12, visible persistence (based on the judgment of a blank) at 2 and 12 c/d, respectively; FLICK2, FLICK12, visible persistence (based on the judgment of a flicker) at 2 and 12 c/d, respectively; CHAS2, CHAS12, flicker fusion at 2 and 12 c/d, respectively; AGAP15, AGAP100, auditory gap detection at 15 and 100 msec, respectively; ATOJ15, ATOJ75, ATOJ200, auditory temporal order judgment at 15, 75, and 200 msec, respectively; ISA, ICA, irregular words accuracy, single/contiguity condition; PSA, PCA, phonologically regular pseudowords accuracy, single/contiguity condition; IST, ICT, irregular words reaction time, single/contiguity condition; PST, PCT, phonologically regular pseudowords reaction time, single/contiguity condition. $^{*}p < .05$. $^{**}p < .01$.

APPENDIX C (Continued)

AGAP100	ATOJ15	ATOJ75	ATOJ200	ISA	ICA	PSA	PCA	IST	ICT	PST	PCT
1.000											
.156	1.000										
.291**	.649**	1.000									
.149	.703**	.614**	1.000								
−.007	.045	−.026	−.012	1.000							
.110	−.061	.033	.034	.409**	1.000						
−.145	−.134	−.180	−.091	.152	.043	1.000					
−.161	−.185	−.209	−.220	.406**	.089	.694**	1.000				
−.046	.035	.039	.009	.049	.153	.076	.222	1.000			
−.097	−.087	−.190	−.053	.009	.095	.110	.119	.734**	1.000		
.005	.054	.043	.114	.083	.226*	−.002	.126	.713**	.587**	1.0000	
−.009	.030	−.084	.018	.038	.149	−.126	−.079	.639**	.619**	.785**	1.000

(Manuscript received March 1, 2006;
revision accepted for publication May 17, 2007.)