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The reading ability of good and poor temporal processors among a group of college students

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In this study, we examined whether good auditory and good visual temporal processors were better than their poor counterparts on certain reading measures. Various visual and auditory temporal tasks were administered to 105 undergraduates. They read some phonologically regular pseudowords and irregular words that were presented sequentially in the same ("word" condition) and in different ("line" condition) locations. Results indicated that auditory temporal acuity was more relevant to reading, whereas visual temporal acuity was more relevant to spelling. Good auditory temporal processors did not have the advantage in processing pseudowords, even though pseudoword reading correlated significantly with auditory temporal processing. These results suggested that some higher cognitive or phonological processes mediated the relationship between auditory temporal processing and pseudoword reading. Good visual temporal processors did not have the advantage in processing irregular words. They also did not process the line condition more accurately than the word condition. The discrepancy might be attributed to the use of normal adults and the unnatural reading situation that did not fully capture the function of the visual temporal processes. The distributions of auditory and visual temporal processing abilities were co-occurring to some degree, but they maintained considerable independence. There was also a lack of a relationship between the type and severity of reading deficits and the type and number of temporal deficits.

The term *temporal processing* refers to the "discrimination of brief, temporally proximate or temporally varying sensory stimuli" (Walker, Hall, Klein, & Phillips, 2006, p. 126). Many dyslexics and language-impaired participants—particularly those who have phonological or concomitant deficits—are impaired in processing rapidly presented sensory events (Lovegrove, Martin, & Slaghuis, 1986; Stein & Talcott, 1999). The events include a range of visual and auditory temporal tasks (Borsting et al., 1996; Heath, Hogben, & Clark, 1999; Slaghuis & Ryan, 1999; Tallal & Stark, 1982; Tallal, Stark, & Mellits, 1985a; Witton et al., 1998). Nevertheless, some recent studies also produced conflicting findings (J. D. Edwards, Walley, & Ball, 2003; Schulte-Körne, Deimel, Bartling, & Remschmidt, 2004).

Therefore, this study investigated how normal adult readers with different visual and auditory temporal abilities processed various reading measures. Although some research has suggested that dyslexics differ from garden-variety poor readers "qualitatively" (Rutter & Yule, 1975), there is growing consensus that the disorder may represent the lower end of an undemarcated continuum of reading ability and is not so distinct from normal reading with respect to some reading, cognitive, and temporal processes (Au & Lovegrove, 2001b; Conlon, Sanders, & Zapart, 2004).

Although many studies have examined how poor reading ability affects one's temporal resolution, only a few studies have investigated how temporal capabilities affect an individual's reading ability. Share, Jorm, Maclean, and Matthews (2002) found that disabled readers with early temporal deficits are no less proficient on later phonological and reading measures than those without early temporal impairment. However, some studies have shown that participants with better temporal processing ability are also better readers subsequently (Benasich & Tallal, 1996, 2002; Facoetti & Lorusso, 2000; Hood & Conlon, 2004; Lyytinen et al., 2005; Rose, Feldman, Jankowski, & Futterweit, 1999; Trehub & Henderson, 1996). Cornelissen et al. (1998) showed that good coherent-motion detectors were more accurate in letter-position encoding, even when reading, age, and IQ were controlled for. Similarly, Pammer, Lavis, and Cornelissen (2004) demonstrated that children with poor frequency-doubling sensitivity read more accurately when words were presented singularly rather than in a whole-text format. Nevertheless, the timing tasks share little variance with phonological sensitivity and contribute little unique variance to word reading (Chiappe, Stringer, Siegel, & Stanovich, 2002; Talcott et al., 2002).

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Thus, the first aim of the present study was to investigate whether normal adults with better auditory and visual temporal capabilities were also better readers and spellers.

Recently, "the umbrella term 'temporal processing' encompasses fundamentally different sensory or cognitive processes that may contribute differentially to language and reading performance" (Walker et al., 2006, p. 126). For instance, Wilmer, Richardson, Chen, and Stein (2004) found that a deficit in detecting coherent motion was associated with reading accuracy, whereas a deficit in discriminating velocities was associated with slow performance of the reading tests. Rapid visual processing or motion sensitivity is related to orthographic skills and irregular words. Conversely, rapid auditory processing and FM sensitivity are associated with phonological skills and phonologically regular pseudowords (Au & Lovegrove, 2001a; Booth, Perfetti, MacWhinney, & Hunt, 2000; Talcott et al., 2000).

Therefore, we next investigated whether readers with better visual temporal processing ability are better at reading irregular words, and whether readers with better auditory temporal processing ability might be better on the pseudowords.

Interestingly, visual temporal resolution is primarily involved in reading text rather than single words (Chase, Ashourzadeh, Kelly, Monfette, & Kinsey, 2003). This is because saccadic eye movement is needed to move from one word to another when reading normal text. Recent studies have shown that the dorsal stream is sensitive to high conductive velocity and that rapid stimulus changes are instrumental in generating saccades. However, the dorsal-stream ("where") processes are suppressed during saccades, whereas the ventral-stream ("what") processes that extract fine details within single fixations in reading (Livingstone & Hubel, 1988) are not (Irwin & Brockmole, 2004). Hence, for a reader who already has visual temporal deficits, such deficits will be more apparent in saccadic suppression. This makes such readers vulnerable to a reading condition that requires saccadic eye movement. On the other hand, reading single words does not require much saccadic movement; therefore, poor visual temporal processors are less vulnerable to this reading situation. This explains why disabled readers find it more difficult to read whole text (Hill & Lovegrove, 1992), whereas poor visual temporal processors find it easier to process single words (Pammer et al., 2004).

Apart from reading whole text, poor readers should also have difficulty reading words presented sequentially in different locations ("line" condition). This difficulty occurs because of the involvement of saccades—and hence, the visual temporal processes—under this reading situation. An example of this is to read some letter strings presented in series of six words underneath corresponding symbols from left to right. The six symbols are spatially apart, and only one word is presented underneath its corresponding symbol each time (see Figure 1). We expected poor visual temporal processors to have difficulty processing such a reading situation. This issue has been overlooked in the literature and will be examined in the present study.

Consequently, we finally investigated whether normal adult readers with better visual temporal resolution would be better at reading words presented sequentially in different locations (line condition that required saccades) as compared with words presented sequentially in the same location ("word" condition). Such differences might be more obvious in irregular words than in pseudowords, given their orthographic characteristics (Au & Lovegrove, 2001a).

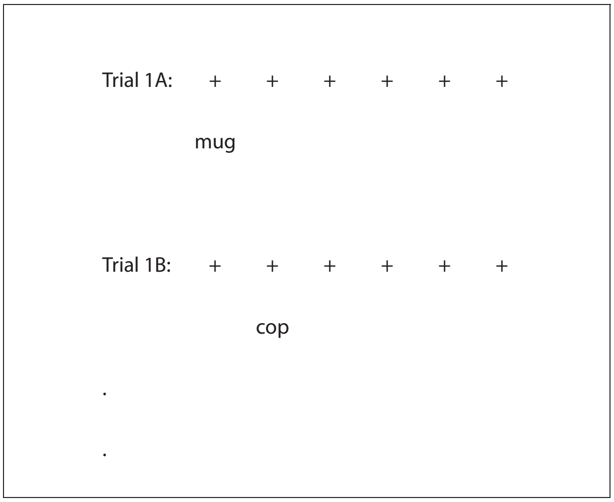

Figure 1. Illustration of the "line" condition in word reading.

METHOD

Participants

A total of 105 English-speaking undergraduate psychology students (ages 17–55; 33 males and 72 females) 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 a reading disability.

This study adopted the visual and auditory tests that are most commonly used in assessing the function of the temporal processes in the literature. Poor readers are impaired at flicker contrast sensitivity (FSEN) (Cornelissen, Richardson, Mason, Fowler, & Stein, 1995; V. T. Edwards et al., 2004; Keen & Lovegrove, 2000), visual gap detection (VGAP) (Boden & Brodeur, 1999; Martos & Marmolejo, 1993; Slaghuis & Lovegrove, 1985), auditory gap detection (AGAP) (Hari & Kiesila, 1996; Hautus, Setchell, Waldie, & Kirk, 2003; McCroskey & Kidder, 1980), and auditory temporal order judgment (ATOJ) (Cacace, McFarland, Quimet, Schrieber, & Marro, 2000; Heiervang, Stevenson, & Hugdahl, 2002; Mody, Studdert-Kennedy, & Brady, 1997). Originally, a visual temporal order judgment (VTOJ) task (May, Williams, & Dunlap, 1988; Walker et al., 2006) was performed in order to create a parallel version of the ATOJ. However, the pilot study showed that this task was not as good as the FSEN in differentiating participants. Given the difficulty in requiring the participants to come back for so many testing sessions, we could only assign two visual and two auditory temporal tasks. Also, the gap detection task had both the visual and auditory versions. Ideally, both tasks should adopt the same tracking method. However, the visual gap detection task was presented in a tachistoscope. Given its technical and programming constraints, a random staircase method was used in the tachistoscope to track the participant's gap detection threshold. Thus, the tracking method was different from Wetherill and Levitt's (1965) procedure used in the AGAP task.

An auditory temporal processing index (AUDINDEX) was calculated by averaging the *z* scores of the thresholds of the auditory tasks. Participants with lower thresholds (in milliseconds) in auditory gap detection and a lower stimulus onset asynchrony (SOA, in milliseconds) in auditory temporal order judgment were considered readers with good auditory temporal processing ability (lower AUDINDEX). Those who scored at or below the 25th percentile in AUDINDEX were considered good auditory temporal processors, whereas those who scored at or above the 75th percentile were considered poor auditory temporal processors. Using these criteria, 26 participants in each of the two groups were identified.

The same algorithm was used to classify participants into good and poor visual temporal processors, taking the average of the *z* scores of all visual thresholds to calculate the visual temporal index (VISINDEX). Participants with lower contrast threshold in the flicker sensitivity task and lower visual gap detection thresholds (in milliseconds) were considered readers with good visual temporal processing ability (lower VISINDEX). Twenty-six participants were identified in the good and in the poor VISINDEX groups.

In particular, within the group of good auditory temporal processors ($n = 26$), 9 of them were good visual temporal processors, whereas 4 of them were poor visual temporal processors; the remaining 13 fell in the middle. Similarly, within the group of poor auditory temporal processors ($n = 26$), 9 of them were poor visual temporal processors, whereas 4 of them were good visual temporal processors; the remaining 13 fell in the middle. Nevertheless, a statistical test on the association across modalities was not significant for either group [$\chi^2(2) = 3.85, p > .05$]. This result indicated that participants who had better temporal processing ability in one modality were not more likely to also have better temporal processing ability in the other modality. Conversely, those who had poor temporal processing ability in one modality were not more likely to also have poor temporal processing ability in the other modality. The results suggest a degree of independence between temporal processing capabilities in the two modalities.

Stimuli, Apparatus, and Procedure

The study consisted of four experimental sessions. The first session consisted of the Advanced Raven's Progressive Matrices (IQ; Raven, 1962), which measure the nonverbal reasoning skills in adults. The second session consisted of the Wide Range Achievement Test (WRAT) reading and spelling subtests (Wilkinson, 1993), followed by the word reading tasks that are illustrated in Measure 3 (below). The third session consisted of VGAP, AGAP, and ATOJ tasks. The last session consisted of the FSEN task. Test conditions were counterbalanced within each session. The experiments were undertaken with the understanding and written consent of each participant according to the guidelines of the human research ethics committee in the university.

Measure 1A: FSEN

The test measured participants' contrast thresholds of sinusoidally flickering fields presented in temporal frequencies of 2 and 12 Hz, subtended at a visual angle of 5º. Viewing was binocular throughout at a distance of 57 cm from a Tektronix 608 X–Y display. The fields were generated on the X–Y display by a P31 phosphor in an Innisfree Picasso CRT Image Generator. 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). The stimulus duration was 1 sec. 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.

Participants were instructed to report on which interval (1 or 2) a flickering rather than a blank field was presented. One field was presented in the first interval, followed by the other presented in the second. Accuracy rather than response time (RT) was emphasized in the task. Feedback and practice were given. The order of presentation for both conditions (2 and 12 Hz) was counterbalanced.

Measure 1B: VGAP

The test measured participants' ability to detect a gap within alternating vertical square wave gratings of spatial frequencies of 2 and 12 cycles/degree (c/deg). The stimuli completely filled a 6.74º × 4.53º target field. On each trial, the gratings were generated by a tachistoscope for 200 msec and were alternated with a variable blank interstimulus interval (ISI) for 10 cycles. The luminance was held constant at 4.8 cd/m^2 across all spatial frequency changes. The binocular viewing distance was 129 cm. Participants had to report the presence or absence of a clear blank interval between the gratings. Accuracy rather than response latency was stressed. The dependent variables were the blank ISIs, and they were recorded using a random staircase method. Feedback and practice were given. The order of presentation for both conditions (2 and 12 c/deg) was counterbalanced.

Measure 2A: AGAP

The test measured participants' ability to detect a gap between two bursts of noise, with both bursts lasting either 15 or 100 msec. The stimuli consisted of continuous white noise or paired bursts of noise that were separated by a gap of variable duration (ISI). They were generated by the National Semiconductor MM5837 digital noise source and a Realistic STA-76 IC/FET AM/FM stereo receiver. They were presented to participants through Sony MDR CD250 headphones at 60 dB SPL. In order to ensure that the participants could hear the noise properly, they were presented with three pairs of noise bursts and were asked whether they had heard the stimuli clearly. Because of the difficulty in getting access to the testing facility, no complete audiological examination was carried out.

On each trial, participants heard either two small bursts of noise followed by a single burst of noise, or the opposite. Their task was 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 it was recorded using Wetherill and Levitt's (1965) procedure. Accuracy rather than RT was stressed. Feedback and practice were given. The order of presentation for both conditions (15 and 100 msec) was counterbalanced.

Measure 2B: ATOJ

The test measured participants' ability to detect the order of two different sine wave tones (a high tone [2200 Hz] and a low tone [400 Hz]) 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 durations of the second, plus the SOA. The stimuli were generated by two Novatech DDS3 Digital Synthesiser boards in the dual-tone generator, and they were presented at 60 dB SPL using the same equipment of the auditory gap detection task. In order 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 whether they had heard the stimuli clearly. Because of a difficulty in getting access to the testing facility, no complete audiological examination was carried out.

On each trial, the participant had to determine whether the high or low tone was presented first. The SOA to distinguish the tone order was the dependent variable, and it was recorded using Wetherill and Levitt's (1965) procedure. Accuracy rather than RT was emphasized. Feedback and practice were given. The order of presentation for the conditions (15, 75, and 200 msec) was counterbalanced.

Measure 3: Irregular and Phonologically Regular Pseudoword Reading

This task required participants to read aloud the irregular words and phonologically regular pseudowords presented sequentially (1) in the same location (word condition), and (2) in different locations (line condition that required eye movement) on the computer monitor.

The stimuli included two lists of 30 irregular words and two lists of 30 phonologically regular pseudowords. 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 Language Proficiency Battery test book (Woodcock, 1984). Both the irregular words and phonologically regular pseudowords were matched in word and syllable length, and multisyllabic words were used to avoid ceiling effects in adult readers. The mean word lengths of the two lists of irregular words were 5.37 and 5.23, whereas those of the two lists of phonologically regular pseudowords were 5.07 and 4.87. Due to the constraints in matching the word and syllable length, the mean frequencies of occurrence of the two lists of irregular words were 45.91 and 34.11 (Baayen, Piepenbrock, & van Rijn, 1993).

There were two modes of text presentation: sequentially presented in the same location (word condition) and sequentially presented in different locations (line condition). In the word condition, a single word was presented in the center of the screen on each trial, and 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 was similar to the rapid serial visual presentation format (RSVP; Bourne, Young, & Angell, 1986; Juola, Tiritoglu, & Pleunis, 1995). There were 12 practice trials and 30 experimental trials.

In the line condition, six crosses were presented evenly from left to right on the screen, which they subtended at a visual angle of 20º between the first and the last cross. A word appeared below each cross successively on each trial. Participants had to follow the crosses and read the words as accurately and as quickly as possible. 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. An illustration of the task is shown in Figure 1.

In the word condition, the words were presented sequentially in the same location, with the next word's display triggered by the voice key detecting the pronunciation of the previous one. In the line condition, the words were not presented continuously (as they are, e.g., when we read a book). They were presented sequentially, with the same timing as that with the word condition. The only difference was that the line condition required saccadic eye movement because the words were horizontally displaced and were not presented in the same location as in the word condition.

Given the constraints of individual differences in reading time, stimulus presentation was "self-paced" in order to ensure that participants had enough time to figure out reading each word in both reading tasks. Self-correction was not allowed because of technical constraints. Thus, accuracy rather than response latency was stressed. Pronunciation accuracy (the dependent variable) was scored for each word. The percentage of accuracy for each list (condition) was calculated [(total score/30) × 100%].

The irregular words and phonologically regular pseudowords were presented both in the word and in the line formats, resulting in four experimental conditions: irregular words presented in the word format (IWORD), irregular words presented in the line format (ILINE), phonologically regular pseudowords presented in the word format (PWORD), and phonologically regular pseudowords presented in the line format (PLINE). The order of the presentation of the conditions was counterbalanced. As was stated in the introduction, visual temporal processing is more closely related to irregular words (Au & Lovegrove, 2001a). Visual temporal acuity also plays a role in a reading condition that requires saccadic eye movement (Chase et al., 2003; Hill & Lovegrove, 1992; Pammer et al., 2004). Hence, we used the conditions above to see whether readers with better visual temporal processing ability (lower VISINDEX) would process the line condition (condition that required saccades) more accurately than the word condition, especially for irregular words. Also, we examined the relationship between auditory temporal processing and pseudoword reading.

RESULTS

Table 1 presents the means and standard deviations of the reading, spelling, and IQ data of both the good and the poor auditory temporal processing readers.

Results confirmed that the good auditory temporal processors had better temporal processing ability (lower AUDINDEX) than did the poor auditory temporal processors [$t(50) = -12.41, p < .05$]. Consistent with our hypothesis, they were also better readers [$t(50) = 4.53, p < .05$] and spellers [$t(50) = 4.6, p < .05$], and had higher nonverbal IQs [$t(50) = 2.34, p < .05$].

Table 1
Means and Standard Deviations of the Data of the Good and Poor Auditory Temporal Processors (ATP)

	Good ATP (n = 26)		Poor ATP (n = 26)		Group Difference	
	M	*SD*	*M*	*SD*	$t(50)$	*p*
IWORDA	79.10	8.36	72.18	11.27		
ILINEA	77.95	7.84	69.74	9.19		
PWORDA	82.69	10.24	73.97	15.52		
PLINEA	84.74	7.31	75.38	13.47		
IQ	114.5	11.63	106.23	13.8	2.34	.023
WRAT-R	110.88	5.55	102.77	7.26	4.53	.000
WRAT-S	113.77	5.94	104.81	7.95	4.6	.000
AUDINDEX	−0.68	0.2	0.92	0.63	−12.41	.000

Note—IWORDA, irregular word accuracy word condition (%); ILINEA, irregular word accuracy line condition (%); PWORDA, pseudoword accuracy word condition (%); PLINEA, pseudoword accuracy line condition; IQ, nonverbal reasoning skills measured by the Advanced Raven's Progressive Matrices; WRAT-R, Wide Range Achievement Test reading scores; WRAT-S, Wide Range Achievement Test spelling scores; AUDINDEX, auditory magnocellular index.

A mixed factorial ANOVA with group (good vs. poor temporal processors) as the between-subjects factor and word type (irregular word vs. pseudoword) and presentation format (word vs. line) as within-subjects factors was performed, taking IQ as the covariate. There was no significant difference in word type [$F(1,49) = 0.88, p > .05$] and no significant word type × IQ [$F(1,49) = 0.41, p > .05$] interaction. The nonsignificant word type × group [$F(1,49) = 0.39, p > .05$] interaction showed that good auditory temporal processors did not seem to have the advantage in reading pseudowords. There was no significant difference in presentation [$F(1,49) = 0.14, p > .05$], and no significant presentation × IQ [$F(1,49) = 0.14, p > .05$] or presentation × group [$F(1,49) = 0.15, p > .05$] interaction. There were also no significant word type × presentation [$F(1,49) = 2.53, p > .05$], word type × presentation × IQ [$F(1,49) = 1.87, p > .05$], and word type × presentation × group [$F(1,49) = 0.06, p > .05$] interactions. The main effect of IQ was not significant [$F(1,49) = 1.07, p > .05$]. However, the main effect of group was significant: Good auditory temporal processors were more accurate than their poor counterparts in word reading across conditions [$F(1,49) = 11.27, p < .05$].

Table 2 shows that the good visual temporal processors were better than the poor group in VISINDEX [$t(50) = -19.92, p < .05$], spelling [$t(50) = 2.07, p < .05$], and IQ [$t(50) = 3.38, p < .05$]. However, unlike the good auditory temporal processors, they did not differ significantly on reading [$t(50) = 1.32, p > .05$].

The mixed ANOVA showed no significant difference in word type [$F(1,49) = 1.5, p > .05$]. There was no significant word type × IQ [$F(1,49) = 0.85, p > .05$] interaction. The nonsignificant word type × group [$F(1,49) = 0.02, p > .05$] interaction suggested that good visual temporal processors did not seem to have

Table 2
Means and Standard Deviations of the Data of the Good and Poor Visual Temporal Processors (VTP)

	Good VTP (n = 26)		Poor VTP (n = 26)		Group Difference	
	M	*SD*	*M*	*SD*	$t(50)$	p
IWORDA	79.74	7.05	74.74	10.63		
ILINEA	78.72	7.12	74.1	9.44		
PWORDA	82.56	8.96	79.87	11.72		
PLINEA	83.59	9.14	80.26	10.06		
IQ	116.38	9.7	105.65	12.98	3.38	.001
WRAT-R	108.88	6.22	106.35	7.56	1.32	n.s.
WRAT-S	111.46	5.71	107.54	7.79	2.07	.044
VISINDEX	−0.91	0.25	1.03	0.43	−19.92	.000

Note—IWORDA, irregular word accuracy word condition (%); ILINEA, irregular word accuracy line condition (%); PWORDA, pseudoword accuracy word condition (%); PLINEA, pseudoword accuracy line condition; IQ, nonverbal reasoning skills measured by the Advanced Raven's Progressive Matrices; WRAT-R, Wide Range Achievement Test reading scores; WRAT-S, Wide Range Achievement Test spelling scores; VISINDEX, visual magnocellular index.

the advantage in processing irregular words. There was no significant difference in presentation [$F(1,49) = 2.11$, $p > .05$], and no significant presentation × IQ [$F(1,49) = 2.15$, $p > .05$] interaction. The nonsignificant presentation × group [$F(1,49) = 0.49$, $p > .05$] and word type × presentation × group [$F(1,49) = 0.11$, $p > .05$] interactions indicated that good visual temporal processors were not more accurate in reading words presented in the line condition, especially for irregular words. There were also no significant word type × presentation [$F(1,49) = 0.06$, $p > .05$] and word type × presentation × IQ [$F(1,49) = 0.02$, $p > .05$] interactions. Neither the effect of IQ [$F(1,49) = 3.7$, $p > .05$] nor that of the main group [$F(1,49) = 1.42$, $p > .05$] was significant. The latter result suggests that good visual temporal processors were not more accurate than their poor counterparts in word reading across conditions.

In sum, good auditory temporal processors were better than poor auditory temporal processors in reading and spelling. Nevertheless, they showed no advantage in processing pseudowords. On the other hand, good visual temporal processors were only better spellers and not better readers. They showed no advantage in processing irregular words and words presented sequentially in different locations (line condition).

Further analyses were performed to compare the reading performance of (1) temporal processors who were good in both the visual and auditory modalities ($n = 9$), (2) temporal processors who were poor in both the visual and auditory modalities ($n = 9$), (3) temporal processors who were poor in the visual but good in the auditory modality ($n = 4$), and (4) temporal processors who were good in the visual but poor in the auditory modality ($n = 4$). The first two groups were those that were either good or deficient in both modalities, whereas the last two groups were those that were deficient only in one but not in the other modality. Probably because of the small sample size, the four groups did not differ in WRAT reading [$F(3,22) = 2.57$, $p > .05$], WRAT spelling [$F(3,22) = 2.34$, $p > .05$], or IQ [$F(3,22) = 1.58$, $p > .05$] (see Table 3).

The mixed ANOVA showed no significant difference in word type [$F(1,21) = 0.21$, $p > .05$]. There were no significant word type × IQ [$F(1,21) = 0.03$, $p > .05$] and word type × group [$F(3,21) = 1.17$, $p > .05$] interactions. There was no significant difference in presentation [$F(1,21) = 0.42$, $p > .05$]. Neither the presentation × IQ [$F(1,21) = 0.34$, $p > .05$] nor the presentation × group [$F(3,21) = 1.86$, $p > .05$] interaction was significant. There were also no significant word type × presentation [$F(1,21) = 1.34$, $p > .05$], word type × presentation × IQ [$F(1,21) = 0.99$, $p > .05$], and word type × presentation × group [$F(3,21) = 0.33$, $p > .05$] interactions. Neither the effect of IQ [$F(1,21) = 2.86$, $p > .05$] nor main group differences [$F(3,21) = 1.41$, $p > .05$] were significant.

Although extreme group analyses are quite common, they are known to increase the chances of Type I error by magnifying differences that do not exist under certain circumstances (Maxwell, 2004). Since reading problems are more likely to be represented within a continuum than in categories, Pearson correlation coefficients and a partial correlation taking IQ into account were computed on the

Table 3
Means and Standard Deviations of the Data of the Temporal Processors Who Were Good or Poor in Either Modality

	Good ATP and VTP (n = 9)		Poor ATP and VTP (n = 9)		Good ATP and Poor VTP (n = 4)		Poor ATP and Good VTP (n = 4)		Group Difference	
	M	*SD*	*M*	*SD*	*M*	*SD*	*M*	*SD*	$F(3,22)$	p
IWORDA	81.85	7.09	74.81	11.91	67.5	10.67	70	5.45		
ILINEA	77.78	6.87	70	9.57	70	7.2	71.67	8.39		
PWORDA	83.33	5.53	76.3	15.67	85	8.82	74.17	12.87		
PLINEA	82.59	7.95	77.04	12.41	88.34	3.33	82.5	8.77		
IQ	115.33	5.2	108.22	13.33	102.5	12.45	108.25	10.31	1.58	n.s.
WRAT-R	111.44	5.59	103.56	8.53	112.50	7.85	104.5	7.33	2.57	n.s.
WRAT-S	114.78	5.31	105.78	9.54	109.75	5.12	110.75	6.18	2.34	n.s.

Note—ATP, auditory temporal processors; VTP, visual temporal processors; IWORDA, irregular word accuracy word condition (%); ILINEA, irregular word accuracy line condition (%); PWORDA, pseudoword accuracy word condition (%); PLINEA, pseudoword accuracy line condition; IQ, nonverbal reasoning skills measured by the Advanced Raven's Progressive Matrices; WRAT-R, Wide Range Achievement Test reading scores; WRAT-S, Wide Range Achievement Test spelling scores.

Table 4
Pearson Correlation Among the Temporal and Reading Measures ($N = 105$)

	IWORDA	ILINEA	PWORDA	PLINEA	WRAT-R	WRAT-S	IQ
FSEN2	−.112	−.133	−.091	−.051	−.064	−.039	−.100
FSEN12	−.159	−.077	−.106	−.094	−.080	−.088	−.127
VGAP2	−.102	−.183	−.016	−.032	−.109	−.269**	−.165
VGAP12	−.059	−.061	−.025	.030	−.012	−.061	−.224*
AGAP15	−.118	−.131	−.318**	−.343**	−.191	−.127	−.194*
AGAP100	−.128	−.155	−.162	−.227*	−.270**	−.305**	−.021
ATOJ15	−.236*	−.278**	−.305**	−.293**	−.346**	−.340**	−.172
ATOJ75	−.171	−.25*	−.274**	−.261**	−.334**	−.329**	−.201*
ATOJ200	−.175	−.269**	−.272**	−.222*	−.365**	−.420**	−.212*

Note—IWORDA, irregular word accuracy word condition (%); ILINEA, irregular word accuracy line condition (%); PWORDA, pseudoword accuracy word condition (%); PLINEA, pseudoword accuracy line condition; WRAT-R, Wide Range Achievement Test reading scores; WRAT-S, Wide Range Achievement Test spelling scores; IQ, nonverbal reasoning skills measured by the Advanced Raven's Progressive Matrices; FSEN2, flicker contrast sensitivity at 2 Hz; FSEN12, flicker contrast sensitivity at 12 Hz; VGAP2, visual gap detection at 2 c/deg; VGAP12, visual gap detection at 12 c/deg; AGAP15, auditory gap detection at 15 msec; AGAP100, auditory gap detection at 100 msec; ATOJ15, auditory temporal order judgment at 15 msec; ATOJ75, auditory temporal order judgment at 75 msec; ATOJ200, auditory temporal order judgment at 200 msec. $^{*}p < .05$. $^{**}p < .01$.

data of all 105 participants. The results in Tables 4 and 5 converge to the same pattern. Corroborating the results of the extreme group analyses, lower visual gap detection thresholds at low spatial frequency (VGAP2) were significantly associated with higher spelling scores and not with higher reading scores. The auditory temporal processing measures correlated significantly with various reading and spelling scores. The results verified why good auditory temporal processors were better readers and spellers, whereas good visual temporal processors were only better spellers. In addition, there were more significant correlations between the auditory measures and pseudoword reading than between the auditory measures and the irregular word measures. An overview showed that better auditory temporal resolution was related to higher pseudoword reading accuracies. However, such findings did not coincide with those of the extreme group analyses, because good auditory temporal processors did not have the advantage in processing pseudowords.

DISCUSSION

In sum, normal adult readers with good auditory temporal processing ability were better than those with poor auditory temporal processing ability in reading, spelling, and IQ. In contrast, good visual temporal processors were only better spellers and not better readers, even though they had higher IQs. Nevertheless, the good auditory temporal processors were not significantly better at reading pseudowords, despite the fact that there were more significant correlations between the auditory and pseudoword measures. Readers with better visual temporal acuity did not seem to have the advantage in processing irregular words and words presented sequentially in different locations (line condition).

Cornelissen et al. (1998) and Pammer et al. (2004) found that good visual temporal processors were also better letter-position encoders and better text readers. The present study extended their findings by demonstrating

Table 5
Partial Correlation Among the Temporal and Reading Measures After Controlling for IQ ($N = 105$)

	IWORDA	ILINEA	PWORDA	PLINEA	WRAT-R	WRAT-S
FSEN2	−.090	−.108	−.074	−.038	−.047	−.019
FSEN12	−.132	−.040	−.084	−.077	−.058	−.064
VGAP2	−.062	−.141	.015	−.010	−.081	−.244*
VGAP12	−.001	.009	.018	.063	.030	−.017
AGAP15	−.072	−.076	−.292**	−.325**	−.162	−.092
AGAP100	−.127	−.156	−.161	−.227*	−.271**	−.307**
ATOJ15	−.201*	−.240*	−.282**	−.275**	−.325**	−.317**
ATOJ75	−.126	−.202*	−.245*	−.240*	−.309**	−.301**
ATOJ200	−.127	−.219*	−.242*	−.199*	−.340**	−.394**

Note—IWORDA, irregular word accuracy word condition (%); ILINEA, irregular word accuracy line condition (%); PWORDA, pseudoword accuracy word condition (%); PLINEA, pseudoword accuracy line condition; WRAT-R, Wide Range Achievement Test reading scores; WRAT-S, Wide Range Achievement Test spelling scores; FSEN2, flicker contrast sensitivity at 2 Hz; FSEN12, flicker contrast sensitivity at 12 Hz; VGAP2, visual gap detection at 2 c/deg; VGAP12, visual gap detection at 12 c/deg; AGAP15, auditory gap detection at 15 msec; AGAP100, auditory gap detection at 100 msec; ATOJ15, auditory temporal order judgment at 15 msec; ATOJ75, auditory temporal order judgment at 75 msec; ATOJ200, auditory temporal order judgment at 200 msec. $^{*}p < .05$. $^{**}p < .01$.

that normal adult readers with better auditory temporal resolution were better on reading and spelling. Conversely, good visual temporal processors were only better spellers and not better readers. Our discrepancy with Pammer et al. could be explained by the use of adults rather than children as participants. Children have a more dynamic temporal sensitivity because of a longer developmental time course of the dorsal visual stream (Mitchell & Neville, 2004). Our findings suggest that auditory temporal processing seemed to be more relevant to reading, whereas visual temporal processing seemed to be more relevant to spelling. Bruck and Waters (1988, 1990) found that phonological processing deficits were associated with spelling difficulties. Nevertheless, partial visual cues (Frith, 1980) and visual memories (Burden, 1992) are also involved in adult spellers. This is because adult spellers are more fluent in reading and prefer the use of a whole-word visual recognition strategy (Bryant & Bradley, 1980).

The results provide further evidence that rapid sensory processes continue to play a role in reading—even in adulthood. Moreover, dyslexia may represent the lower end of a continuum of reading ability, since better temporal skills are associated with better reading skills in both normal and disabled readers (Au & Lovegrove, 2001b; Witton et al., 1998). Our results fit with the latter studies because these studies also isolated auditory temporal processing and showed that it had a larger impact on reading than visual temporal processing. The findings also echoed those of Huslander et al. (2004), Reed (1989), and Tallal (1980); English-speaking poor readers were more likely to have auditory and not visual deficits.

Previous findings showed that the auditory mechanisms are dominant in the processing of nonsense words or pseudowords, whereas rapid visual processing is dominant in the processing of irregular words (Au & Lovegrove, 2001a; Booth et al., 2000; Talcott et al., 2000). The present study, nevertheless, was supportive only of the former result and not of the latter. Farmer and Klein (1995) proposed that auditory versus visual temporal deficits might lead to different patterns of reading problems, with auditory deficits leading to phonological dyslexia and visual deficits leading to surface dyslexia (or a mixed pattern). Our results partially echoed those of Farmer and Klein by showing a close relationship between auditory temporal resolution and pseudoword reading, but not between visual temporal resolution and irregular word reading among the correlation coefficients.

Moreover, readers with better auditory temporal resolution were not significantly better on phonologically regular pseudowords. Although the ability of the auditory cortex to process perceptual tasks that require precise timing (Kelly, Rooney, & Phillips, 1996; Phillips & Farmer, 1990; Tallal, 2003) is relevant to the development of phonological sensitivity and grapheme–phoneme assimilation (Laasonen, Service, & Virsu, 2002; Pammer & Vidyasagar, 2005; Tallal, Stark, & Mellits, 1985b), the present findings imply that auditory temporal acuity may not be causal to pseudoword reading. Higher cognitive or phonological processes might have mediated the correlation between auditory temporal processing and pseudowords. Our findings are consistent with those of Rosen (2003), who suggested that auditory deficits appear not to be causally related to dyslexia. The auditory deficits are only associated with a reading disability because of the lack of a relationship between the severity of the deficits and language impairment. Hence, phonological and reading impairment co-occur with an optional sensorimotor syndrome (Ramus, 2004).

The present study also did not support Farmer and Klein's (1995) speculation that visual deficits lead to surface dyslexia. First, visual temporal processes did not correlate significantly with irregular word reading. Second, good visual temporal processors—when compared with their poor counterparts—were not more accurate in reading irregular words. Talcott et al. (2002) illustrated the difficulty in isolating the phonological and orthographic processes. Since the sensory measures only contribute minimally to the reading processes and the covariation between various cognitive and reading skills is more common in normal adults than in children, significant group differences in the processing of irregular words and pseudowords with respect to their presentation format may be too subtle to be picked up.

Farmer and Klein (1995) suggested that visual and auditory temporal processing deficits co-occur. Therefore, we investigated whether readers who had good temporal capabilities in one modality also had good temporal capabilities in the other modality, and whether those who had poor temporal capabilities in one modality also had poor temporal capabilities in the other modality. A statistical test on the association across modalities, however, did not support this suggestion. There was no significant difference on the distribution of good ($n = 9$), average ($n = 13$), or poor ($n = 4$) visual temporal processors within the group of good auditory temporal processors ($n = 26$). Similarly, within the group of poor auditory temporal processors ($n = 26$), there was no significant difference on the distribution of poor ($n = 9$), average ($n = 13$), or good ($n = 4$) visual temporal processors. Therefore, the distributions of auditory and visual temporal processing abilities are co-occurring to some degree, but they maintain considerable independence.

We also broke down our samples into four groups: (1) temporal processors who were good in both the visual and auditory modalities ($n = 9$), (2) temporal processors who were poor in both the visual and auditory modalities ($n = 9$), (3) temporal processors who were poor in visual but good in the auditory modality ($n = 4$), and (4) temporal processors who were good in visual but poor in the auditory modality ($n = 4$). We were interested to see whether participants who were better temporal processors in both modalities (Group 1) were better than those who were good at one but deficient in the other modality (Group 3 or 4) in reading and spelling. We also investigated whether the latter groups (3 and 4) were better than those who were deficient in both modalities (Group 2). Probably because of a small sample size, we failed to find any significant group differences. Farmer and Klein (1995) predicted a larger difference in pseudoword reading, between the good and poor auditory temporal processors. In addition, a larger difference in irregular word reading should be obtained between the good and poor visual temporal processors. Those with both temporal deficits should have the greatest deficits. Our results, however, failed to support Farmer and Klein's predictions. A comparison of the first two groups (those who were good in both modalities and those who were poor in both modalities) did not seem to show any significant differences in reading both types of words. For instance, readers having deficits in both modalities did not seem to be worse than those having auditory deficits but good visual temporal resolution. Yet, there was a trend that readers having good temporal resolution in both modalities scored higher than those who had one or both temporal deficits. An overview of the last two groups (those who were poor in visual but good in auditory vs. those who were good in visual but poor in auditory) did not show any significant modality preference in processing the two types of words. There was a trend for those who had good auditory temporal resolution but visual deficits to score higher in pseudowords. However, those who had good visual temporal resolution but auditory deficits did not seem to score higher in irregular words. Thus, there was a lack of a relationship between the type and severity of reading deficits and the type and number of temporal deficits. An increase in sample size, along with comparing good readers who are good temporal processors and poor readers who are poor temporal processors, may yield significant differences.

This study demonstrated that adults with better temporal resolution—in particular, better auditory temporal resolution—performed better on reading, spelling, and IQ tasks. It is possible that better temporal resolution developmentally enhances these abilities; that is, stronger fluid abilities enhance the acquisition of crystallized abilities. One area that requires further discussion is the possibility that the initial group differences were more a function of reading, spelling, and IQ abilities than of temporal resolution. However, results in the mixed ANOVA showed a significant group difference in word reading among the auditory temporal processors—driven mainly by temporal processing ability—even when taking IQ into account. The correlation analyses indicated a consistent relationship between temporal processing and various reading and spelling measures—even when the variance of IQ associated with these variables was controlled for. Hence, temporal processing still plays a role in adult reading, even though its influence is not as strong as those of reading, spelling, and IQ.

Chase et al. (2003), Hill and Lovegrove (1992), and Pammer et al. (2004) showed that word reading that requires saccadic eye movement is related to visual temporal acuity. Therefore, we investigated whether normal adult readers with better visual temporal resolution were better on words presented sequentially in different locations (the line condition, which required saccades) as compared with words presented sequentially in the same location (the word condition). Although the stimuli used in the present experiment were still sequences of unrelated words and the line condition did not measure normal text reading, such a word reading condition demands certain control in eye movement and should be suitable for testing visual temporal sensitivity. Nevertheless, our results failed to support this hypothesis. It is possible that saccades are affected only by deficient but not by excessive temporal ability.

By the time we ran our experiment, we were unable to administer motion studies because of the constraints in equipment and programming. Motion studies—such as frequency doubling (Pammer et al., 2004) or motion stimuli (Conlon et al., 2004; Scheuerpflug et al., 2004)—may yield significant differences in the visual temporal and reading processes. We wanted to find out whether these temporal and reading variables mattered within a normal population. Such a difference was not observed in the normally progressing range of readers. Because of the attenuated group difference in temporal sensitivity, the discrepancy between reading normal text and single words might have been less obvious.

Mitchell and Neville (2004) showed that the dorsal visual stream pertinent to visual temporal processing is more plastic than the ventral stream; it takes a longer developmental time course across the early school years. Adults may have a less dynamic temporal sensitivity as compared with children. Consequently, low-level rapid sensory processes are less important to reading in adults.

Finally, the line presentation was not really that continuous and did not provide much stimulation for saccadic eye movement as compared with the whole-text format. Thus, it might not have been as effective as would have been natural reading of whole text in capturing the full function of the visual temporal processes.

In conclusion, this study indicated that readers with good auditory temporal processing ability were significantly better than those with poor auditory temporal processing ability in reading, spelling, and IQ. In contrast, readers with better visual temporal acuity were only better spellers and not better readers. This result illustrated that auditory temporal resolution was more relevant to reading, whereas visual temporal resolution was more relevant to spelling. Good auditory temporal processors did not have the advantage in processing pseudowords, even though pseudoword reading correlated significantly with auditory temporal processing. The results suggested that some higher cognitive or phonological processes mediated the relationship between auditory temporal processing and pseudoword reading. Good visual temporal processors did not have the advantage in processing irregular words. Likewise, they did not process words presented sequentially in different locations (line condition) more accurately than words presented sequentially in the same location (word condition). The discrepancy might be attributed to the use of normal adult readers and the unnatural reading situation that had not fully captured the function of the visual temporal processes. Contradicting the prediction from Farmer and Klein (1995), the distributions of auditory and visual temporal processing abilities were co-occurring to some degree, but they maintained considerable independence. There was also a lack of relationship between the type and severity of reading deficits and the type and number of temporal deficits.

AUTHOR NOTE

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