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Crossmodal Temporal Order and Processing Acuity in Developmentally Dyslexic Young Adults

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We investigated crossmodal temporal performance in processing rapid sequential nonlinguistic events in developmentally dyslexic young adults (ages 20–36 years) and an age- and IQ-matched control group in audiotactile, visuotactile, and audiovisual combinations. Two methods were used for estimating 84% correct temporal acuity thresholds: temporal order judgment (TOJ) and temporal processing acuity (TPA). TPA requires phase difference detection: the judgment of simultaneity/nonsimultaneity of brief stimuli in two parallel, spatially separate triplets. The dyslexic readers' average temporal performance was somewhat poorer in all six comparisons; in audiovisual comparisons the group differences were not statistically significant, however. A principal component analysis indicated that temporal acuity and phonological awareness are related in dyslexic readers. The impairment of temporal input processing seems to be a general correlative feature of dyslexia in children and adults, but the overlap in performance between dyslexic and normal readers suggests that it is not a sufficient reason for developmental reading difficulties.

Key Words: developmental dyslexia; temporal order judgment; temporal processing; crossmodal; visual; auditory; tactile.

INTRODUCTION

In a previous study, we found that not only unimodal but also crossmodal temporal input processing is impaired in developmentally dyslexic children compared to normally reading children (Laasonen, Tomma-Halme, Lahti-Nuuttila, Service, & Virsu, 2001). Simultaneity vs nonsimultaneity of light flashes and clicks was judged in audiovisual experiments, of flashes and skin indentations in visuotactile experiments, and of clicks and indentations in audiotactile experiments. We now report a corresponding impairment in developmentally dyslexic adults. Several methodological improvements were possible in the experiments with adults and two different methods were used for evaluating temporal processing abilities. Relations to various reading-related tasks were also investigated.

Many, if not most, cognitive tasks require processing across multiple perceptual modalities. Events in our inner and outer environment pose constraints on the rate at which these crossmodal processes must advance or complete. Language and reading make no exception, being explicitly crossmodal and time constrained, requiring

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fast and accurate integration of sequential perceptual information within and between various modalities in windows of milliseconds. Accordingly, developmental language impairment (e.g. Tallal & Piercy, 1973a, 1973b; Tallal, Stark, & Mellits, 1985; see, however, Bishop, Carlyon, Deeks, & Bishop, 1999; Segalowitz, 2000; Zhang & Tomblin, 1998) and, more specifically, developmental dyslexia (cf. reviews Farmer & Klein, 1995; von Euler, Lundberg, & Llinás, 1998) have been associated with impaired, mainly unimodal, perceptual temporal acuity as a coexisting or contributing factor to the linguistic difficulties.

Development and aging modify basic perceptual temporal acuity, the ability to distinguish temporally discrete events. This has been demonstrated both unimodally (vision: Di Lollo, Arnett, & Kruk, 1982; audition: Irwin, Ball, Kay, Stillman, & Rosser, 1985; Werner, Marean, Halpin, Spetner, & Gillenwater, 1992; Wightman, Allen, Dolan, Kistler, & Jamieson, 1989; tactile perception: Petrosino & Fucci, 1989; Woodward, 1993) and crossmodally (Lewkowicz, 1996). Also, linguistic perception, at least partly relying on temporal cues, develops gradually in early infancy. At the age of one month infants can discriminate between a wide variety of speech sounds that acoustically differ only by events lasting tens of milliseconds (Eimas, Siqueland, Jusczyk, & Vigorito, 1971). Before the age of one year, the phonological characteristics of the child's language environment have modified this ability so that discriminating between phonological categories expressed in the mother tongue is refined (Kuhl, Williams, Lacerda, Stevens, & Lindblom, 1992) and discriminating between categories not functional in the native language becomes gradually more difficult (Cheour et al., 1998; Werker & Tees, 1984).

On the other hand, a group of children with a genetic risk for dyslexia differed in processing phonological information based on temporal cues at the age of less than one week (Leppänen, Pihko, Eklund, & Lyytinen, 1999). Later such groups have demonstrated less differentiation in categorical perception of familiar phonemes (Degelder & Vroomen, 1998; Manis et al., 1997) and other difficulties in phonological processing (Mann, Cowin, & Schoenheimer, 1989; Vellutino, 1987). Adequate phonological awareness, the awareness of syllables in words, onsets and rhymes, and phonemes (Swan & Goswami, 1997; Witton et al., 1998), has been repeatedly shown to be related to emerging reading ability (Bradley & Bryant, 1978, 1983; Goswami, 1993, 1999).

Development of language comprehension does not involve the auditory modality alone. The dialogue between auditory and visual modalities in language perception and acquisition can be observed in infancy. Children, ages less than 6 months, can recognize the concordance between auditory and visual speech sounds and are influenced by visual input when interpreting auditory speech (Rosenblum, Schmuckler, & Johnson, 1997; Kuhl & Meltzoff, 1982). This reciprocal relationship strengthens during development depending on the specific language environment (Desjardins, Rogers, & Werker, 1997; Massaro, Cohen, & Smeele, 1995; Massaro, Thompson, Barron, & Laren, 1986) and is prominent in adults (McGurk & MacDonald, 1976). Reading-disabled children, on the other hand, have been shown to be impaired in audiovisual speech integration (Degelder & Vroomen, 1998).

When children are actually learning to read, the requirement for rapid sequential crossmodal processing becomes even more obvious. Visual and auditory processing are related to grapheme–phoneme conversion, the application of correspondence rules between printed letters and letter combinations and their phonological equivalents. This is not the only crossmodal processing involved in reading, however. When reading aloud, for example, one has to program, retain, and execute at a millisecond level the eye movements needed for sequentially deciphering the printed characters. In parallel with this process, a conversion from vision to phonology and semantics takes place. At the same time the reader has to program motor sequences for verbal output, as well as retain and execute proper movements. The resulting speech is monitored through auditory feedback, and articulator positions and movements are corrected with the aid of kinesthetic/tactile perception. In addition to this direct contribution of crossmodal processes, crossmodal processing not directly related to the cognitive sequences of reading is required at the same time. For example, one has to maintain position during reading and inhibit irrelevant stimulation within and between various modalities. Therefore, accurate and fast crosstalk at least between visual and auditory, visual and tactile, and auditory and tactile modalities is necessary. Developmental impairment in crossmodal temporal acuity might well contribute to difficulties in various cognitive abilities.

We investigated here whether dyslexic young adults suffer from temporal processing impairment in several perceptual systems, including audiotactile, visuotactile, and audiovisual modalities. We also studied how performance levels in different systems are related and whether the results between systems differ. If developmental dyslexia is considered to result from a developmental lag, then it is expected that the group differences found in our earlier study concerning crossmodal temporal processing of dyslexic children (Laasonen et al., 2001) would have ameliorated toward adulthood. Temporal acuity was investigated with two methods, one tapping temporal order judgments (TOJ) and the other temporal processing acuity (TPA) in which order judgments were not required. Although oral language consists of ordered speech sounds and rapidly changing cues, it is currently not known to what extent such order is perceived in real time or reconstructed in time windows of up to 100 ms (Saberi & Perrott, 1999). Some language impairments could be associated with the need for more time to reconstruct stimulus order rather than manifest an inability to process rapid changes. Thus, the two methods may yield different results as TPA is not concerned with explicit order judgments. We further investigated how crossmodal temporal performance, both in normally reading and dyslexic readers, is related to linguistic processes and reading.

METHODS

The methods were essentially the same as in Laasonen et al. (Laasonen, Service, & Virsu, 2001). The essential aspects are explained below.

Participants

Participants were 16 developmentally dyslexic adults (ages 20 to 36 years) and a control group of 16 age-matched normal readers, all volunteers without known neurological deficits. The two groups did not differ statistically significantly with respect to a number of demographic variables (age, education, handedness, sex) as reported in our previous study (Laasonen et al., 2001). The participants were selected from a larger sample and matched so that all performed at least at the level of average ability in the revised form of the Wechsler adult intelligence scale (Wechsler, 1992) on both the verbal and the performance scales. The groups did not differ statistically significantly in any of the intelligence quotients (Laasonen et al., 2001). There was, however, a trend in favor of the control group in the performance and full scores.

Neuropsychological Assessment

Wechsler Memory Scale Revised (WMS-R): Associative learning. The associative learning test of the WMS-R was administered for assessment of verbal memory functions (Wechsler, 1997). In this test participants are read aloud eight pairs of words, half of which are easy to associate (e.g., eye–ear) and the other half more difficult to associate (e.g., pony–telephone). After list presentation the first word from each pair is given as a verbal cue by the experimenter and the participant is asked to recall its correct associate. The list is presented three times. We recorded the total number of words correctly recalled.

Reading-related tasks. To be classified as dyslexic, participants had to report a history of reading difficulties and to perform at least one standard deviation worse than the control group mean in at least three reading-related tasks.

Auditive discrimination was evaluated with a list of 12 three-syllable sequence-pairs (e.g., /keteke/–/kedeke/). The pairs were presented using a tape recorder and the participant judged after each pair whether the sequences were similar or dissimilar. Dissimilar pairs differed with regard to one phoneme. Number of correct answers was recorded.

In the *phonological synthesis* task, tape-recorded sequences of individual phoneme sounds making up a word were presented. After each series the participant was asked to name the word containing the phonemes [e.g., the participant heard the Finnish phonemes /p/, /a/, /l/, /l/, and /o/, and named the word ''pallo'' (ball)]. The number of correct answers was recorded.

Naming speed was assessed with the Rapid Alternating Stimulus Naming (RAS) task (Wolf, 1986). In this a 50-item matrix of numbers, letters, and colors is presented. The participant is told to name them as quickly as possible. The task was administered twice. The time in seconds on the second trial was recorded.

Reading speed was evaluated with a text which was read aloud, as fast as possible, for 1 min. Number of words correctly read was recorded.

Lexical decision with a priming word was assessed in a computerized task. It assessed the speed at which a participant decided whether a displayed string of four to six black capital letters, subtending about 1.7 degrees in height and forming a well-legible word, was a real Finnish word or not. The test comprised 142 trials, which all started with a cue: a black cross appeared for 500 ms in the middle of a white computer screen (Power Macintosh 7500, Apple 15'' monitor) to begin a trial. A priming word appeared immediately after the cue at the same spatial location for 200 ms. The priming word was either semantically related to the next word or not. The second word, immediately presented until a response, was the target word for lexical decision. The target word was either covered or uncovered by a high-contrast masker grating (occurrence probability 0.5, spatial frequency about 3.3 c/deg). The task was always, however, to make a decision, as fast as possible, whether the target string was a word or nonword. Participants responded with a two-alternative yes/no response ''word'' by pressing the ''m'' key on a standard keyboard and ''nonword'' by pressing the ''c'' key. Mean reaction times were recorded for the target words after the exclusion of incorrect and deviant answers (more than two standard deviations above or below the individual mean).

Word segmentation speed was assessed with a list of 78 letter strings, consisting of two to four conjoint words (Lindeman, 1998). The task was to mark as many word boundaries in the strings as possible in 3 min [e.g., ''vastatatarjota'' (''answeroffer'') with the correct segmentation ''vastata|tarjota'' (''answer|offer'')]. The number of correct segmentations was recorded.

Reading comprehension was evaluated with one fictional and one factual text. The participants read the texts and answered multiple-choice questions, assessing comprehension of details/facts, word/phrases, cause–result/order, main idea/meaning, and ability to draw conclusions/make interpretations (Lindeman, 1998). One text was read at a time. The number of correct answers was recorded.

Letter rotation was assessed with an 84-trial computerized task. The participant assessed whether a displayed, clearly visible tilted letter (capital F, L, or R) was a normal letter or its mirror image. The rotation angle varied between 0 and 180 degrees, in 30-degree steps (12 to 14 trials with each angle). The height of the high-contrast letters subtended about 10 degrees in height. The target letter appeared in the middle of a computer screen (technical details as in the lexical decision task) and lasted until a correct response was given. The participant responded with a yes/no response ''normal'' by pressing the space key on a standard keyboard and ''mirror'' by pressing key ''b.'' Reaction times were recorded after the incorrect and deviant responses were excluded (more than two standard deviations above or below the mean).

Nonword span was assessed with sequences consisting of CVCV nonwords. A tape recorder presented the stimuli and the participant repeated each presented sequence (e.g., /potu-hine/, /sile-hine/). Five sequences of each length were presented. The number of correct answers and span (the longest sequence of nonwords repeated correctly) were recorded.

Temporal order judgment. Temporal performance was assessed as temporal acuity measured with two different methods in three crossmodal perceptual systems (for demonstration, see http://www.helsinki.fi/hum/ylpsy/neuropsy.html. The readers of both groups were able to perform the psychophysical tasks equally as their results were similar in several nontemporal aspects of the temporal acuity experiments (Laasonen et al., 2001). Acuity was considered to increase when thresholds in milliseconds decreased.

The TOJ task is illustrated in Fig. 1A. Thresholds were determined for three crossmodal combinations: audiotactile, visuotactile, and audiovisual. For half of the participants, the tasks were presented in the order mentioned above, and for the other half in reversed order. The stimulus pulses were indentations

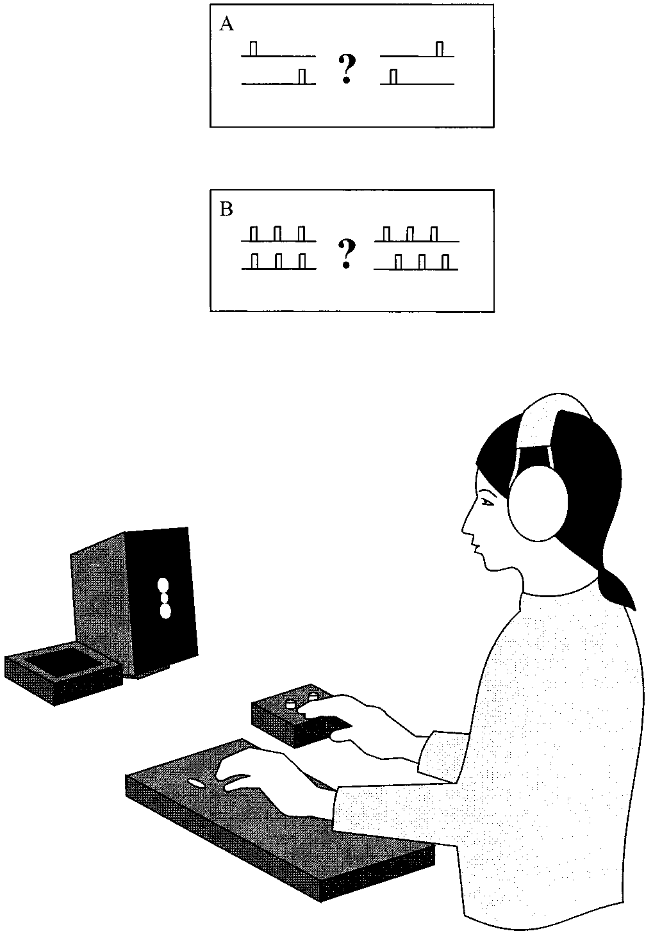

FIG. 1. Apparatus and procedure in audiotactile experiments. Stimulus pulse alternatives of the TOJ tasks are illustrated in (A). The participant judged whether the sound burst on the headphones or the indentation to left index finger was delivered first. Stimulus pulse alternatives of TPA tasks are displayed in (B). The participant judged whether the pulses of the auditory and tactile modality occurred simultaneously or nonsimultaneously when they were presented in phase or out of phase.

of the left index finger in the tactile modality, brief tone bursts in the auditory modality, and flashes of light in the visual modality.

One stimulus pulse was delivered in each perceptual modality and the participants were instructed to estimate in each TOJ task in which modality the stimulus pulse occurred first. The two pulses never overlapped. The response was given by pushing one key in a panel for ''x modality first'' and another one for ''y modality first.'' The probability for ''x first'' was 0.5. About 0.5 s after the response, the next stimulus pair followed without explicit feedback. Participants were advised to respond as carefully as possible and the responses were not speeded. The task was commenced again if the participant reported a mistake.

The execution of the experiment was computerized (Laasonen et al., 2001). An adaptive yes/no threshold search with varying stimulus onset asynchronies (SOA) was used to estimate the SOA with a probability of 0.84 for correct responses (Wetherill & Levitt, 1965). This was the *temporal order judgment threshold.* SOA was 500 ms at the beginning of each task. If the response regarding the order of pulses was correct, the SOA decreased by 0.05 log units. After an incorrect answer SOA increased by 0.05 log units. Following the first reversal, the SOA increased after each incorrect and decreased after four successive correct answers by 0.05 log units. The first two reversals were not included in the analyses, and the average of 12 reversals provided an estimate for the 84% correct threshold. At the beginning of a task, when the interval between stimuli was long, the task was easy. As the SOA gradually decreased, the performance became random. If the participants were unsure of the correct answer, they were instructed to guess.

In the *audiotactile* task the participant judged whether an 8-ms tone burst in the auditory modality or an indentation to the skin of the finger tip in the tactile modality was presented first. The tactile stimuli were delivered to the tip of the left index finger by means of the blunt tip of a solenoid axis. The maximum amplitude of the indentation was 2 mm and its force about 0.9 N. Another solenoid acted in antiphase with the stimulus solenoid and made its sound noninformative as a cue. The solenoids were embedded in a soft padding, which attenuated their sound. The participant used headphones, which further attenuated the clicking sound of solenoids by 30 dB. Auditory stimuli were presented binaurally through headphones at about 60 dB SPL. The 8-ms tones were square waves at 4 kHz without phase-locking and smoothing.

In the *visuotactile* task the participant estimated whether a flash of light in vision or an indentation of the finger tip in the tactile modality occurred first. Tactile stimuli were as above. Visual stimulus pulses were produced by a green (565 nm) diffused light emitting diode (LED). The LED was 8 mm in diameter, subtending 0.5 degrees in visual angle at its 90-cm viewing distance. The background of the LED was matte black and subtended 12×5 degrees. Each flash lasted 8 ms. The luminance of the flash was about 4 cd/m^2 and that of the background 1.5 cd/m^2. Participants fixated the stimulus LED.

In the *audiovisual* task the participants judged whether a burst in the auditory modality or a flash in vision was presented first. Visual stimuli were as above but now the tone bursts (about 65 dB SPL at the participants ears) were delivered on a loudspeaker situated in front of the participant.

Temporal processing acuity. The TPA estimation was as similar to TOJ as possible and with the same modality combinations. The same stimuli were used but now the number of stimulus pulses in each modality was three. The temporal phase of the two parallel triplets was judged: was it the same or different in the two trains (Fig. 1B). The pulses of the triplets were either in the same physical phase (pulses simultaneous) or in antiphase (pulses 180 degrees phase-shifted). The participants were instructed to judge, after each presentation of the two triplets, whether the stimulus pulses were simultaneous or not (Virsu, 1997). They responded by pushing one key for ‘‘pulses simultaneous’’ and another one for ‘‘pulses nonsimultaneous.’’ With long temporal distances (SOAs) between pulses, the task was easy, and with short temporal distances (SOAs), the responses became random. The probability of simultaneity was 0.5.

The same adaptive yes/no threshold determination method as for TOJ was used for estimating the 84% correct SOA threshold, the *temporal processing acuity threshold.* At the beginning of each task, one pulse per second was delivered in each pulse triplet of each channel. Hence, the onset asynchrony (SOA) of stimulus pulses *within separate triplets* was 1000 ms. When presentation was simultaneous, the SOA between stimulus pulses of separate triplets was zero. When the presentation was nonsimultaneous, the SOA difference *between pulses of the two triplets* was 500 ms, which corresponds to the SOA measured in TOJ.

In the *audiotactile* task the participants judged whether the three indentations of the left index finger tip were simultaneous or not with three tone bursts in the auditory modality. In the *visuotactile* task the participant evaluated the simultaneity or nonsimultaneity of three flashes of light and three indentations of the left index finger tip. In the *audiovisual* task the comparison of simultaneity and nonsimultaneity was made between three tone bursts and three flashes of light.

Statistical Analyses

The distribution properties of variables was investigated. All variables, including their transformations (logarithmic and *z*-standard score), were screened for outliers and tested for normality and homogeneity of variances. We report the analyses made with the original variables, since the transformations did not essentially change the results. To investigate the differences in performance between the normal and the dyslexic readers we used MANOVA and mixed ANOVA. Since it was *a priori* assumed that the dyslexic readers' performance would be impaired compared to the control group (cf. reviews Farmer & Klein, 1995; von Euler et al., 1998), the differences in individual tasks between the groups were analyzed with one-tailed t tests (correction for different variances made when required). In other instances two-tailed t-test p values are presented. In reading task comparisons the variables were transformed so that larger values indicated better performance (-(variable) transformation, when needed) and then to T scores (mean 50, standard deviation 10). Correlations presented were calculated as Pearson product moment correlations with logarithmically transformed variables to achieve linearity. Principal component analyses were based on these correlations. In principal component analyses the variables were transformed also so that larger values indicate better performance (-(variable) transformation, when needed). Scree plots of eigenvalues (at least 1 in accepted factors) and assessment of the percentage of total variation explained ($>$60% in the dyslexic readers) were used to determine the optimal number of components to extract in quartimax rotation.

RESULTS

Group Differences in Reading-Related Tasks

The performance of the dyslexic readers in the reading-related tasks is presented in Fig. 2. The dyslexic readers' performance tended to be inferior in every task and the groups differed in their reading and spelling performance when tested with 2×13 MANOVA (groups $\times$ tasks) ($F(13, 18) = 3.88$, $p < .005$). In two-tailed individual task comparisons, the difference between dyslexic and normal readers was statistically significant in all tasks, except ''letter rotation'' reaction time ($t(30) = 1.29$, $p < .21$), ''reading comprehension—fiction'' score ($t(30) = -1.51$, $p < .15$), and the ''associative learning'' subtest score of WMS-R ($t(30) = -1.50$, $p < .15$).

Group Differences in Temporal Acuity

The thresholds of 84% correct TOJ and TPA judgments are presented in Figs. 3 and 4. The dyslexic readers' average thresholds were longer in every modality combination, but only half of the differences were statistically significant, as the asterisks show. We analyzed the combined results with a three-way mixed ANOVA where reading group (dyslexic/normal), method (TOJ/TPA), and modality combination (audiotactile/visuotactile/audiovisual) were the factors in a $2 \times 2 \times 3$ ANOVA.

The temporal processing performance of the dyslexic readers differed statistically significantly from that of the control group ($F(1, 30) = 7.00$, $p < .02$), although the groups were matched in both performance and verbal IQ. The effect of the assessment method, TOJ or TPA, was statistically highly significant ($F(1, 30) = 41.68$, $p < .0001$). However, there was no significant main effect of modality combination ($F(2, 60) = 0.24$, $p < .80$). There was a significant interaction between assessment method and modality combination, however ($F(2, 60) = 26.19$, $p < .001$). In the audiotactile

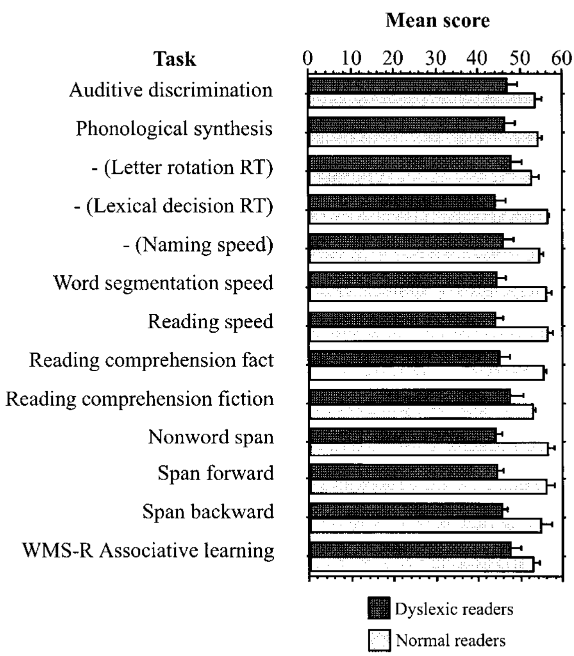

FIG. 2. Performance in different reading-related tasks for dyslexic and normal readers. The variables presented are *T*-score transformed over the two groups and (-(variable))-transformed as indicated so that larger value in every case indicates better performance. The bars represent group mean scores. The error bars indicate one standard error of the mean (*SEM*). RT, reaction time.

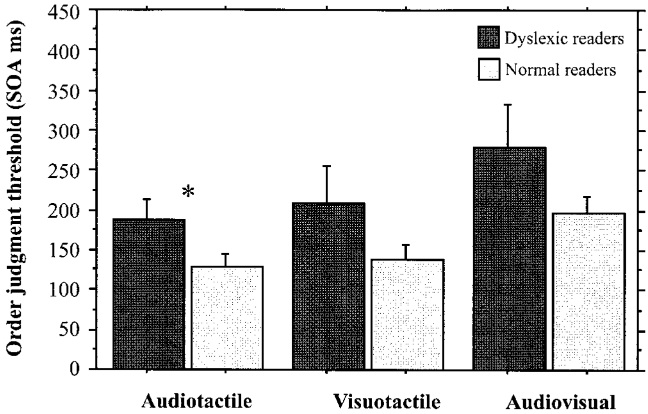

FIG. 3. The means and *SEM*s of temporal acuity in order judgment tasks (TOJ) in dyslexic (N = 16) and normal (N = 16) readers. The asterisk refers to statistically significant differences ($p < .05$) in one-tailed t tests.

and visuotactile combinations temporal acuity was superior ($N = 32$) in TOJ compared to TPA (audiotactile: $t(31) = 9.04$, $p < .0001$; visuotactile: $t(31) = 5.6$, $p < .0001$). In the audiovisual modality combination TPA and TOJ did not differ significantly ($t(31) = .97$, $p < .4$). The interactions method $\times$ modality $\times$ group, group $\times$ method, and group $\times$ modality were not statistically significant.

To inspect the possibility that group differences resulted from different response strategies we separately assessed in both groups the single responses of each participant in every trial both in TOJ and in TPA experiments. No evidence was obtained that the two groups differed in their responses in this respect.

Temporal order judgment. On average, dyslexic readers required somewhat longer SOAs for correctly judging the order of events in every modality combination but only the audiotactile difference was statistically significant. The shortest SOA was 130 ms in the audiotactile TOJ of normal readers. The corresponding threshold of dyslexic readers was 187 ms. Intermediate SOAs in both groups were obtained in the visuotactile task (in the control group 139 ms and in dyslexic readers 209 ms). The longest SOAs were required in audiovisual order judgment (in the control group

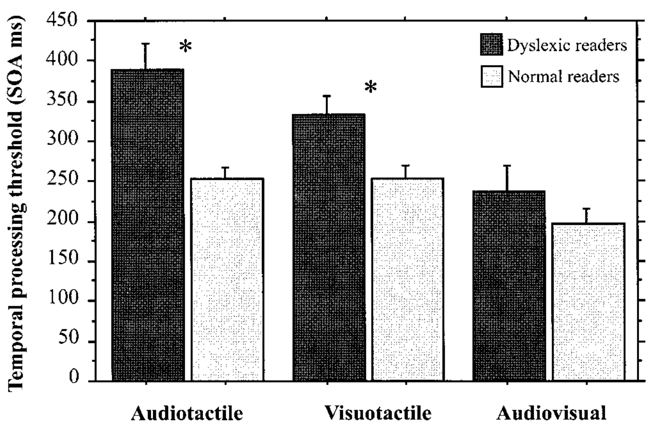

FIG. 4. The means and *SEM*s of temporal acuity in temporal processing acuity tasks (TPA) in dyslexic (N = 16) and normal (N = 16) readers.

196 ms and in dyslexic readers 280 ms). The dyslexic and control groups differed statistically significantly in the audiotactile comparisons ($t(23.88) = 1.97$, $p < .04$) (degrees of freedom corrected for different variances). The statistical trend was evident, however, also in the visuotactile ($t(30) = 1.43$, $p < .09$) and audiovisual tasks ($t(30) = 1.45$, $p < .09$), although these group differences did not reach statistical significance.

Temporal processing acuity. Dyslexic readers had longer SOAs for judging the simultaneity/nonsimultaneity of stimulus pulses in every combination of modalities, but the difference was not statistically significant in the audiovisual task. The SOA for simultaneity/nonsimultaneity judgment of pulses in the two triplets was shortest in the audiovisual comparison. In the normal readers the threshold SOA in this task was 197 ms and in dyslexic readers 236 ms. This means that the control participants distinguished between simultaneous and nonsimultaneous pulse-like audiovisual events 2.54 times per second [1000/(2 × 197)] since one period consists of two stimulus pulses. Dyslexic readers were able to segregate 2.12 events per second in the same task. The threshold SOA in the audiotactile task for the control group was 252 ms (1.98 segregations/s) and in the visuotactile task 254 ms (1.97 segregations/s). In the dyslexic readers, the SOA threshold in the audiotactile task was 388 ms (1.29 segregations/s) and 333 ms (1.5 segregations/s) in the visuotactile task. In individual task comparisons the dyslexic readers performed statistically significantly worse in the audiotactile ($t(20.36) = 3.64$, $p < .001$) (degrees of freedom corrected for different variances) and visuotactile TPA ($t(30) = 2.83$, $p < .005$) than the normal readers. In the audiovisual TPA task, the group difference did not reach statistical significance ($t(30) = 1.05$, $p < .16$).

Although the dyslexic readers required longer SOAs than the normal readers for correct judgments in the tasks on the average, the threshold distributions of the two groups overlapped to a great extent. Figure 5 shows the distributions of acuity thresholds both in TPA and TOJ in dyslexic and normal readers with logarithmically transformed variables, standardized over both groups. The median temporal acuity was inferior (threshold higher) in the dyslexic readers in every task, but not every dyslexic individual's temporal performance was poorer than that of normal readers. Similarly, some normal readers required longer stimulus onset intervals at threshold than many

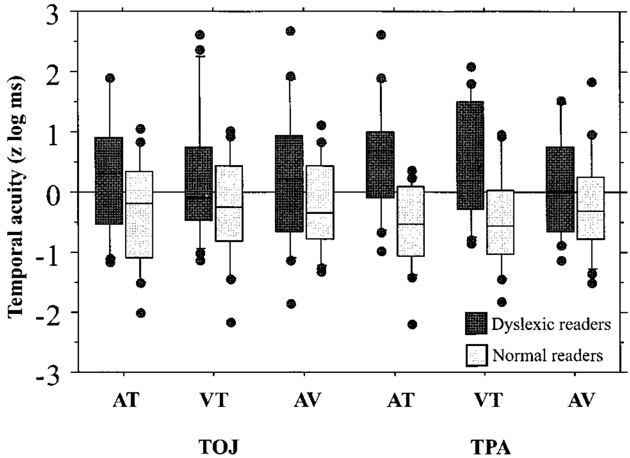

FIG. 5. Distribution of SOA performance in TOJ and TPA tasks for dyslexic and normal readers. The horizontal line in the box plot represents the median of the group, the box 25th to 75th percentiles, the whiskers 10th to 90th percentiles, and the dots individual performances outside these values. The acuity thresholds are logarithmically transformed and standardized over the two groups.

dyslexic readers. The differences between the individuals in the audiotactile and visuotactile TPA tasks were very clear, however.

Correlations between Temporal Acuities

The relationships between the TOJ tasks are presented in Fig. 6A. The dotted line indicates the 0.05 significance level of Fisher's *Z*. Better performance in one modality combination was related to better performance in others. All the correlations were positive, and in the dyslexic readers the correlations tended to be larger than in normal readers.

Figure 6B shows the relationships between the TPA tasks. The correlations differed from those of TOJ comparisons. All the correlations were statistically significant and positive in the dyslexic readers, but none of the correlations reached significance in normal readers.

The relationships between the TPA and TOJ tasks are displayed in Fig. 6C. The correlations were all positive, but only a few reached statistical significance. The same modality combinations between TPA and TOJ were not the most clearly correlated, although in dyslexic readers these modally matching combinations reached statistical significance.

We were able to calculate split-half reliabilities for TOJ and TPA as they were averages of six element thresholds. Guttman split-half reliabilities were calculated from the correlations between acuities estimated from the first six and last six reversals of the threshold search. In the TOJ tasks, these were 0.90 for the audiotactile, 0.81 for the visuotactile, and 0.94 for the audiovisual comparisons of control group, and 0.93, 0.95, and 0.98 in the dyslexic readers, respectively. In TPA tasks, the corre-

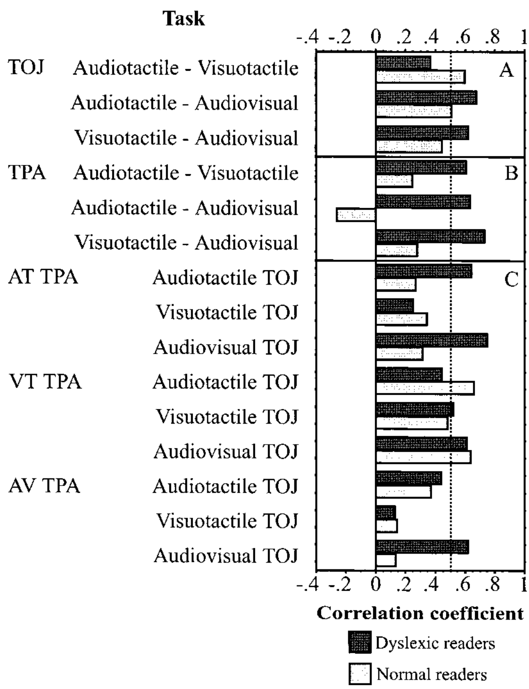

FIG. 6. Pearson product moment correlations between temporal acuities (SOA ms) of modality combinations in TOJ tasks (A), TPA tasks (B), and between TPA and TOJ tasks (C) for dyslexic and normal readers. The variables were logarithmically transformed. The dotted line refers to statistical significance of correlations at $p < .05$.

sponding values for control group were 0.51, 0.81, and 0.86, and for the dyslexic group 0.86, 0.62, and 0.85.

Component Structure of Temporal Acuity and Reading-Related Tasks

The relationships between temporal processing performance and reading-related tasks were assessed separately in the dyslexic and normal readers by means of principal component analyses. Their full loading matrices are presented in Table 1.

Three well-interpretable components were extracted in the dyslexic readers. Figure 7 illustrates the loadings of the first two factors. The first principal component reflected *temporal acuity* and it accounted for 28% of the total variation of the variables. All the temporal acuity tasks were best explained by this component (over 37% of their variance) and it was clearly related to phonological synthesis. The second component, dubbed *processing speed,* explained best all the time-constrained reading-related tasks. The third component reflected *memory* functions, as it best explained the variance of the memory tasks (26% of nonword span, 42% of WAIS-R span forward, 64% of WMS-R associative learning, and 72% of WAIS-R span backward).

In normal readers the component structure was less clear (Table 1). The reading-related tasks were not designed to differentiate between good readers, and the correlations between these tasks as well as between the temporal performance measures were low. As individual variation in the reading related tasks was hard to interpret among normally reading adults, no interpretation of principal components is offered for this analysis.

DISCUSSION

We assessed temporal processing performance in developmentally dyslexic adults and their age- and IQ-matched controls. Thresholds for judging temporal order and simultaneity/nonsimultaneity of stimuli were estimated in audiotactile, visuotactile, and audiovisual perceptual modality combinations. On the average, developmentally dyslexic readers required somewhat longer SOAs to make correct judgments in any task despite the fact that one method required explicit order judgments and the other did not. Thus, the impairment in processing rapidly changing sequential nonlinguistic events was quite general and concerned all the bimodal combinations studied, including those with a tactile component. As reported in our earlier study (Laasonen et al., 2001), the nontemporal psychophysical performance of the dyslexic readers was not poorer in our experiments as compared to normal readers, and therefore, nontemporal aspects cannot explain the group differences of temporal acuity. Temporal acuity as a general feature was strongly related to phonological awareness in developmentally dyslexic adults.

An impairment of temporal acuity in developmental dyslexia has been repeatedly found in earlier studies as reviewed in the Introduction. In the present and our other investigations (Laasonen et al., 2000, 2001), we have extended these studies to the detection of phase differences in periodic stimulus trains, compared different methods, studied developmental dyslexia in children and adults, and used unimodal as well as crossmodal stimuli, including tactile stimulation. With only minor variations, it appears that both temporal order judgment and temporal processing acuity are generally and quite similarly impaired in developmentally dyslexic individuals compared to normal readers. It is especially striking that the impairment is found in pure tactile as well as in crossmodal temporal processing although the tasks do not contain linguistic contents in the usual sense.

Both TOJ and TPA produced essentially similar average results, indicating that temporal input information processing is poorer in dyslexic than normal readers gen-

TABLE 1
Quartimax Raw Rotated Principal Component Solution Separately for the Dyslexic (N = 16) and Normal (N = 16) Readers

		Principal component loadings					
		Dyslexic readers			Normal readers		
Task	Transformation	I	II	III	I	II	III
Letter rotation RT	−(seconds)	0.39	0.75	0.04	0.48	0.12	0.66
Lexical decision RT	−(seconds)	−0.07	0.90	−0.15	0.23	0.54	0.25
Auditive discrimination	+(correct)	0.13	0.25	−0.43	−0.43	−0.74	−0.03
Phonological synthesis	+(correct)	0.59	0.21	−0.18	0.25	0.27	−0.74
RAS	−(seconds)	0.16	0.66	0.04	0.11	−0.55	0.42
Nonword span	+(correct)	−0.01	0.10	0.51	0.32	−0.57	−0.14
Reading speed	+(words/min)	−0.32	0.86	0.20	0.47	−0.57	0.08
WMS-R	+(correct)	0.37	0.02	0.80	0.05	0.49	0.11
WAIS-R span forward	+(correct)	−0.36	0.14	0.65	0.25	0.16	−0.45
WAIS-R span backward	+(correct)	0.01	0.02	0.85	0.02	−0.09	−0.86
TOJ audiotactile	−(logSOA)	0.69	0.00	0.18	0.89	−0.22	0.00
TOJ visuotactile	−(logSOA)	0.61	0.27	0.13	0.75	0.17	0.18
TOJ audiovisual	−(logSOA)	0.84	−0.13	0.26	0.71	0.16	−0.27
TPA audiotactile	−(logSOA)	0.78	−0.16	0.29	0.32	0.47	0.58
TPA visuotactile	−(logSOA)	0.90	0.16	−0.16	0.79	0.04	0.00
TPA audiovisual	−(logSOA)	0.78	−0.26	−0.31	0.39	−0.67	0.08
Explained variance %		28	18	17	23	18	16

Note. Abbreviations used = RT, reaction time; RAS, rapid alternating stimulus naming; WMS—R, Wechsler Memory Scale—Revised; WAIS—R, Wechsler Adult Intelligence Scale—Revised.

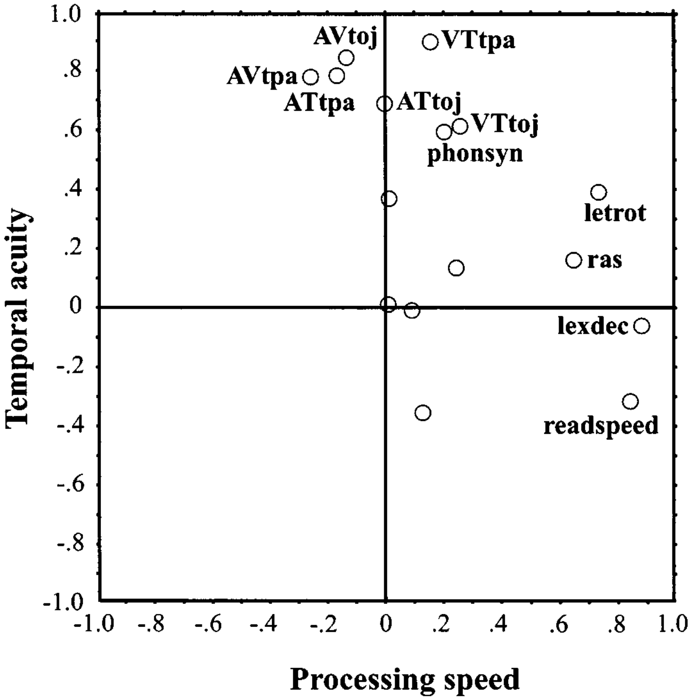

FIG. 7. Loadings of components ''temporal acuity'' (= *y*) and ''processing speed'' (= *x*) in principal component analysis of the dyslexic readers. Loadings of at least 0.5 are marked by the variable names. The remaining variables are indicated by empty circles. Abbreviations: ATtoj, audiotactile TOJ; VTtoj, visuotactile TOJ; AVtoj, audiovisual TOJ; ATtpa, audiotactile TPA; VTtpa, visuotactile TPA; AVtpa, audiovisual TPA; phonsyn, phonological synthesis; letrot, letter rotation; lexdec, lexical decision; ras, naming speed; readspeed, reading speed.

erally, across methods and modalities. However, in the normal readers the correlations between results over individuals were low and the results did not load on a single principal component. Thus it appears that these two methods do not completely measure the same mechanism, a conclusion that was reached also in our study of unimodal variables (Laasonen et al., 2001).

The impairment of crossmodal temporal acuity seems to be a rather common feature of developmental dyslexia. However, as far as we know, there is no unequivocal evidence that this correlation is causal. In fact, the overlap of temporal acuity distributions for dyslexic and normal readers suggests that the relatively poor temporal acuity does not prevent the development of normal reading ability (cf. Bishop et al., 1999).

It is possible that the same underlying factor could cause both reading difficulties and temporal impairment, including clumsiness (Locke, 1998). This factor could have a genetic origin as 2-week-old children with a genetic risk for dyslexia (Leppänen et al., 1999) display temporal impairment. The appearance of temporal processing impairment in dyslexic adults as well as in children suggests that temporal impairment is permanent.

An interesting finding was that temporal acuity, independently of the modality combination and whether the dyslexic and control groups differed in a given task, was positively related to phonological awareness in dyslexic readers. Although this relation was based only on the correlations of 16 subjects in the principal component analysis, the association gains credibility from a similar finding in the study of unimodal tactile, auditory, and visual TOJ and TPA (Laasonen et al., 2001). Hence, at least one important prerequisite for reading development was related to temporal acuity performance in adult dyslexics. It is also of interest that temporal acuity in the principal component analysis was not associated with verbal memory or processing speed.

However, it seems that, in dyslexic readers, temporal acuity without the requirement for order judgments (TPA), was equally, or even more related to phonological processing compared to TOJ. Accordingly, Saberi and Perrott (1999) have recently shown that the perception of order at time intervals less than about 100 ms may not always be crucial for speech intelligibility. Therefore, if one considers temporal acuity impairment to lie behind the phonological awareness difficulties of developmental dyslexia, the impaired perception of temporal relationships of simultaneity/nonsimultaneity or perhaps even a more basic temporal difficulty seems to be as essential as, if not more essential than, the perception of order.

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