Development of Rapid Temporal Processing and Its Impact on Literacy Skills in Primary School Children

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In a longitudinal study, auditory and visual temporal order thresholds (TOTs) were investigated in primary school children (N = 236; mean age at first data point = 6.7) at the beginning of Grade 1 and the end of Grade 2 to test whether rapid temporal processing abilities predict reading and spelling at the end of Grades 1 and 2. Auditory and visual TOTs differed but showed comparable developmental trajectories over 20 months. Visual TOTs were not predictive of literacy measures; auditory TOTs in Grade 1 were the best predictor. Interestingly, they were related to spelling in Grade 2 while auditory TOTs in Grade 2 were not, suggesting that rapid auditory processing abilities have a causal influence on literacy development.

Developmental dyslexia is a specific impairment in learning to read, which does not reflect a general cognitive impairment, and does not result from sensory deficits and/or inadequate schooling (American Psychiatric Association, 1994; Shaywitz, 1998). Current models of literacy development postulate that reading and spelling develop jointly; in different phases of literacy development, reading acts as a pacemaker for spelling, and vice versa (Frith, 1986). Therefore, dyslexia is often accompanied by poor spelling abilities (Shaywitz & Shaywitz, 2005).

Even though it is largely agreed that dyslexia has a neurobiological basis (see Habib, 2000, for review), consensus about its exact etiological basis is still lacking. It has been suggested that temporal processing impairments such as deficits in rapid temporal processing (Tallal, 1980), deficits in the detection of dynamic stimuli (Talcott & Witton, 2002), or deficits in rhythm and stress perception (Goswami, 2011; Goswami et al., 2002) might underlie developmental dyslexia. More recent temporal processing accounts of dyslexia (Goswami, 2011; Goswami et al., 2002; Talcott & Witton, 2002) view dynamic changes within stimuli as the crucial temporal parameters and use tasks measuring coherent motion detection, amplitude modulation detection, frequency modulation detection, or rise time perception, among others, to evaluate temporal processing abilities. In contrast, the classical temporal processing theory of dyslexia by Tallal (1980) views stimulus duration and rapidity of stimulus change as crucial temporal parameters and uses tasks measuring gap detection or temporal order judgment (TOJ), among others, to evaluate temporal processing abilities.

This study used Tallal’s (1980) rapid temporal processing theory of dyslexia as a framework and measured temporal processing abilities with TOJ tasks. Tallal’s (1980) theory assumes that a basic temporal processing impairment leads to an inability to integrate sensory information that converges in rapid succession in the central nervous system. The basic temporal deficit causes a cascade of effects, starting with disruption of the normal development of an otherwise effective and efficient pho-
nological system. These deficits of phonological processing result in subsequent failure to read normally (Tallal, 1980, 2000; Tallal, Merzenich, Miller, & Jenkins, 1998; Tallal, Miller, & Fitch, 1993).

Although originally proposed and extensively studied with respect to rapid auditory perception, the deficit is viewed as occurring also in the visual domain (Tallal, 2000). Indeed, many psychophysical studies support the rapid temporal processing theory by revealing rapid auditory temporal processing deficits (e.g., Groth, Lachmann, Riecker, Muthmann, & Steinbrink, 2011; see Farmer & Klein, 1995, for review), rapid visual temporal processing deficits (e.g., Becker, Elliott, & Lachmann, 2005; see Farmer & Klein, 1995, for review), or both visual and auditory rapid temporal processing deficits (e.g., Laasonen, Service, & Virsu, 2001; van Ingelgem et al., 2001) in dyslexia.

However, there are also a number of psychophysical studies that are not in favor of the rapid temporal processing theory. Some of these studies failed to find support for the pansensory nature of the temporal processing deficit (e.g., Heim, Freeman, Eulitz, & Elbert, 2001). Others did not find a selective impairment for processing tones and/or visual symbols at faster rates in dyslexia (e.g., Chung et al., 2008). Yet others showed that visual and/or auditory problems are not confined to rapid temporal processing (e.g., Caccace, McFarland, Oui-met, Schrieber, & Marro, 2000) or that problems in rapid temporal processing do not necessarily lead to literacy impairment (Landerl & Willburger, 2010). Finally, there are also studies that suggest that there is no rapid temporal processing deficit in dyslexia at all (Nitttrouer, 1999; Schulte-Körne, Deimel, Bartling, & Remschmidt, 1998).

One reason for the conflicting results might be that the rapid temporal processing deficit in dyslexia recovers with age. Hautus, Setchell, Waldie, and Kirk (2003) measured gap detection in four age groups of dyslexic children and adults. Rapid temporal processing deficits were found in the youngest age groups (6–9 years) but not in older children and adults. This result points to a maturational lag in the development of rapid temporal processing abilities. Impairments in temporal resolution might ameliorate with age, whereas its effect, the reading disorder, remains as the temporal deficit disrupted the normal course of reading development.

The results by Hautus et al. (2003) highlight the importance of measuring temporal processing abilities in young children. Early measurement can also help to clarify the role of temporal resolution for the development of reading: If rapid temporal processing abilities measured before reading instruction are predictive for later reading performance, then it can be concluded that rapid temporal processing deficits are the cause rather than the consequence of reading failure (see also Goswami, 2003). It turns out, however, that even results from such longitudinal studies are not clear-cut.

A longitudinal study with a correlational approach (i.e., studying an unselected sample of children) showed that reading performance in school can be predicted by rapid temporal processing abilities: In this study, Hood and Conlon (2004) found that auditory TOJ in preschool and first grade and visual TOJ in first grade predict future reading performance. Some longitudinal studies with a categorical approach (i.e., comparing groups of children who differ concerning reading-related skills or genetic risk for dyslexia) suggest, however, that preschool rapid auditory processing measures do not predict a reading disorder (Boets, Vandermosten, Poelmans, et al., 2011; Heath & Hogben, 2004; Share, Jorm, Maclean, & Matthews, 2002).

The heterogeneous results on the role of rapid temporal processing for reading development and dyslexia might, in part, be explained by the different methods applied: Some studies (e.g., Groth et al., 2011; Hood & Conlon, 2004; Share et al., 2002) used the method of constant stimuli with predefined interstimulus intervals (ISIs) to measure rapid temporal processing abilities. They do not report a psychophysical threshold, but a score based on correct responses. Other studies (e.g., Laasonen et al., 2001; Schulte-Körne et al., 1998; van Ingelgem et al., 2001) computed thresholds, such as temporal order thresholds (TOTs) or gap detection thresholds. Estimation of a threshold requires repeated presentation of critical ISIs. This can be achieved by adaptive procedures in which ISIs are selected on the basis of the participant’s responses in previous trials. These procedures increase the efficiency and reliability of the measurement (see Leek, 2001; Wittmann & Fink, 2004) and might thus be more appropriate to measure temporal processing abilities, especially in studies with young children.

The main aim of this study is to enhance our understanding of the role of rapid temporal processing for the early development of literacy. Former studies (with the exception of Boets, Vandermosten, Poelmans, et al., 2011) focused on reading only and neglected spelling, although current models of literacy development state that reading and spelling develop jointly and influence each other (Frith, 1986). Thus, we will evaluate the predictive role of rapid temporal processing both
for reading and spelling abilities in the early school years. Second, as explained above, measuring rapid temporal processing via the method of constant stimuli might be suboptimal, especially when investigating children. Therefore, with this study we intended to provide reliable measurements of children’s rapid temporal processing abilities by computing psychophysical thresholds using adaptive procedures disguised as age-appropriate computer games. Third, former longitudinal studies on the role of rapid temporal processing for the development of literacy (with the exception of Hood & Conlon, 2004) focused on the auditory domain when measuring rapid temporal processing abilities. In this study we measured both auditory and visual temporal processing to investigate whether rapid temporal processing affects literacy development independently from modality. Finally, to the best of our knowledge, the longitudinal study by Hood and Conlon (2004) is the only one measuring rapid auditory and visual processing at two points in time (preschool and first grade). The period between the measurements was only 6 months, which was sufficient for their particular research questions. To conclude, however, that early rapid temporal processing abilities have an impact on later development of literacy and that a possible correlation does not reflect an interaction in the development of these two abilities, the first measurement of perceptual abilities should be done before literacy instruction and the second measurement when reading and spelling skills are already well established. Only if literacy performance is predicted better by the rapid temporal processing abilities measured before literacy instruction can it be concluded that rapid temporal processing has indeed a causal impact on literacy development. Thus, in this study, rapid auditory and visual processing were assessed twice over a period of about 1½ years (beginning of Grade 1 and last half of Grade 2).

In addition to clarifying the impact of rapid temporal processing abilities on literacy development, the present design allows for conclusions on the development of rapid temporal processing skills as such. There are a number of studies in which the development of rapid temporal processing abilities in childhood was investigated. These studies, however, either did not measure a threshold (Hood & Conlon, 2004), were confined to the auditory domain (Bishop, Carlyon, Deeks, & Bishop, 1999; Boets, Vandermosten, Poelmans, et al., 2011), or applied cross-sectional research designs (Walker, Hall, Klein, & Phillips, 2006). Thus, the longitudinal design of this study gives the unique opportunity to investigate the stability of rapid auditory and visual temporal processing abilities over a time window of 1½ years during childhood and to explore relations between the development of rapid temporal processing abilities in the auditory and the visual modality.

Method

Participants

There were 236 primary school children (121 males, 115 females) participating in this study, who were investigated at various data points in Grade 1 and Grade 2. At the first data point, 2 months after school entry, children were aged between 5;5 and 7;4 (years;months; M = 6;7). Participants had a mean IQ of 108 in the Grundintelligenztest Skala 1 (CFT 1; Weiß & Osterland, 1997), were native speakers of German, and attended Grade 1 for the first time.

The current sample is a subsample of a cohort of 1,411 primary school children who participated in an evaluation study that investigated the predictive validity of a German paper-and-pencil screening instrument (Steinbrink, Schwanda, Klatte, & Lachmann, 2010). All 53 schools enrolled in the evaluation study were rated concerning social status of the school district and rurality. Considering this, 21 schools characterized by different social statuses of the school district were chosen for this study, half of them from a rural environment and half from urban surroundings. To select the participants for this study, 12 children from each class (6 females) were drawn by lot.

The study followed the declaration of Helsinki and was approved by the local ethics committee. Voluntary participation was only possible when a written informed consent signed by the children’s parents was available before the first experimental session. As gratification, children received little toys for their participation.

Measures

All measurements with children were undertaken in the morning in the course of regular school days.

Rapid Auditory and Visual Temporal Processing

The children were assessed two times, at the beginning of Grade 1 and close to the end of Grade 2. Of the 236 children who originally participated, 30 were not available for retesting in Grade 2. Each child was individually assessed in a quiet room in school.
Apparatus. Auditory stimuli were generated by an external digital sound card (Hammerfall DSP Multiface; RME, Haimhausen, Germany) connected to a standard notebook computer. Sample rate was 44.1 kHz, 24 bit in case of basic auditory thresholds, and 16 bit in temporal processing tasks. Sounds were presented via a closed headphone (Beyerdynamic DT 770, Heilbronn, Germany). The headphone was calibrated using an artificial ear system (Bruel & Kjaer Type 4153, Copenhagen, Denmark). Correct output of the sound card was always tested prior to an experimental session using a digital voltmeter. For stimulus delivery and experimental control, the software Presentation (Neurobehavioural Systems Inc., San Francisco, CA) was used.

Visual stimuli were presented on a cathode ray tube (CRT) screen (17′ Adi Modiscan, Adi Corp., Taipei, Taiwan; XVGA, 32 bit color depth) connected to the notebook computer. The frame rate was set to 122 Hz. The children were seated in front of the screen with a distance of 30 cm. In case of visual acuity measurement, the maximum distance of the class room was used (3–5 m; to account for different distances, exact distances were used as calibration factors). Children responded to the experimental trials using an USB numerical key pad. For stimulus delivery and experimental control, the software Presentation (Neurobehavioural Systems Inc., San Francisco, CA) was used.

Basic auditory thresholds and visual acuity. As peripheral visual and hearing deficits might influence the performance in the TOJ tasks, peripheral hearing and visual acuity were measured prior to the TOJ experiments at both data points.

Hearing was assessed monaurally in both ears with pure tone audiometry using four frequencies: 500, 1000, 2000, and 4000 Hz. Each frequency was presented 12 times for 500 ms. Intensities were varied according to a maximum likelihood algorithm (Green, 1993). At both data points seven children had to be excluded from the analysis of the auditory TOJ tasks due to diagnosed hearing impairment (hearing loss of 20 dB and more in two or more of the tested frequencies).

Visual acuity was measured with the Freiburger Visual Acuity Test (Bach, 1996) using a Landolt c with four possible opening directions. At Grade 1 measurement, four children, and at Grade 2 measurement, one child had to be excluded from the analysis of the visual TOJ task due to deficits in visual acuity (.75 or less).

Auditory TOJ task. Auditory and visual TOJ were measured in counterbalanced order. Both the auditory and the visual TOJ task were implemented as age-appropriate computer games to sustain children’s cooperation and attention over the course of the experiment.

The scenario of the auditory TOJ task was inspired by the Sound Order subtest of the Dyslexia Early Screening Test (Fawcett & Nicolson, 1995) as used in a longitudinal study on relations between auditory and visual temporal processing and early reading development by Hood and Conlon (2004). To measure individual thresholds, an adaptive psychophysical procedure was used. Two pure tones (166 Hz 79 dB SPL, 1430 Hz 70 dB SPL, mono) with a duration of 75 ms were successively presented binaurally in randomized order. Stimulus onset asynchrony (SOA) was varied in the range 1–1,000 ms in 16 log steps (10 0.0; 100.2; 100.4; ...; 102.8; 103.0). The lower tone was assigned to a cow, the higher to a mouse. Children were presented...
with a scenario at the screen (Figure 1a) showing the mouse at the left and the cow at the right side to define an assignment to the key pad (cursor left vs. cursor right). They were instructed to listen to the two animal sounds and to indicate which animal was shouting first by a corresponding button press (two-alternative forced choice). In case of correct response, a feedback was given in form of a small ball added to a row of already received balls at the bottom of the screen. Children were trained with 10 presentations, SOA = 398 ms [10^{2.6}] down to 158 ms [10^{2.3}]. The start of each trial was indicated by the appearance of a ball between the two animals. After 200 ms, the presentation of the two tones started. With the response button press, the ball between the animals disappeared and, in case of a correct response, visual feedback was given.

Two consecutive runs were performed with each child. Both experimental runs started with an SOA of 398 ms. In pilot experiments this SOA was determined as unambiguous for children. SOA was then calculated using two independent, two-down-one-up staircases randomly interleaved in log steps. To keep up motivation, every 7th to 13th trial a fail-safe “bonus” trial was interleaved with an SOA of 398 ms. Runs were terminated after 60 trials, regardless of the state of the staircases.

Visual TOJ task. A scenario with a seal was presented (Figure 1b). The seal was placed in the middle of the scene and moved its head to the left and right for 750 ms. After a delay of 500 ms with the seal’s head in middle position one of two colored balls (diameter 7.7°, distance to the seal’s head 14° each, luminance 62 cd m^{-2}, background .7 cd m^{-2}) was presented either at the right or at the left side of the animal. After an SOA of 8 ms up to 492 ms (1–60 frames), the second ball was presented at the other side. Children were instructed to indicate which of the two balls appeared first, by pressing the corresponding key on the key pad (cursor left or right), as the seal should catch the first ball (two-alternative forced choice). In case of correct response, a feedback was given in form of a small ball added to a row at the bottom of the screen. Children were trained with 10 presentations (SOA = 328 ms down to 115 ms).

Two consecutive runs were performed with each child. Both experimental runs started with an SOA of 115 ms (14 frames). Next, SOA was calculated using two independent, two-down-one-up staircases randomly interleaved in linear steps of 33 ms (4 frames). Every 7th–13th trial a “bonus” trial was interleaved with an SOA of 492 ms. Runs were terminated after 30 trials, regardless of the state of the staircases. The staircase procedure of the visual TOJ task differed in details from that of the auditory TOJ task, as a logarithmic adjustment of SOA was not possible with visual stimuli due to the fixed frame rate of the CRT screen. The longer duration of a trial in case of visual TOJ was the reason to terminate already after 30 trials and not after 60 trials as in case of auditory TOJ.

Estimation of auditory and visual TOTs. Auditory and visual thresholds were estimated for each run separately. Responses from both staircases as well as “bonus” trials were collapsed and a logistic psychometric function was fitted to the data using the MATLAB toolbox psignifit (2.5.6; http://bootstrap-software.org/psignifit; cf. Wichmann & Hill, 2001). Threshold was defined as SOA with 75% correct responses.

Threshold measurements were labeled as misses according to the following criteria: (a) negative threshold value, negative slope value, or threshold value larger than SOA of a “bonus” trial (auditory 398 ms, visual 492 ms); (b) slope > 500; and (c) slope > mean slope + 1 SD. In the final analysis, only the best threshold value (lowest SOA) of the two independent runs was included.

Reading and Spelling

Reading and spelling abilities were assessed at the end of Grades 1 and 2 using standardized German reading and spelling tests. Children were tested in a quiet room at their school. For all statistical analyses, raw scores were used.

In Grade 1, two reading tests and one spelling test were administered. The Diagnostischer Lesetest zur Frühdia gnose von Lesestörungen (DLF 1-2; Müller, 1999), a reading test for first and second graders, was used to measure reading accuracy in terms of reading errors (maximum error score = 33). In this test, children have to read aloud real words of varying difficulties (e.g., short vs. long words; words with and without consonant clusters) as well as pseudowords. As a second reading test, the Würzburger Leise Leseprobe (WLLP; Küspert & Schneider, 1998) was used, which measures reading speed for real words in primary school children (maximum number of correctly read words = 140). The WLLP is a speed test measuring silent word reading, in which randomly ordered written words that are very familiar to primary school children (e.g., egg, button, cow) have to be allocated to corresponding pictures (one corresponding picture and three distractors per written word). Children’s task is to read as many words as possible in a limited
time and to mark for each word read the picture corresponding to it. Finally, the *Diagnostischer Rechtschreibtest für erste Klassen* (DRT 1; Müller, 2004a), a spelling test for first graders, was used to investigate children’s spelling abilities. In this test, two little stories are read to the children, who are required to write down 30 defined words from these stories (maximum error score = 30). These easy words all obey regular phoneme–grapheme correspondences in German. Thus, the test measures alphabetic spelling ability.

In Grade 2, one reading test and one spelling test were employed. At this data point, we refrained from measuring reading accuracy a second time (DLF 1-2), as we did not expect to find much variability concerning reading accuracy in a sample of unselected German second-grade children: Reading speed was found to be a better indicator of reading skills in German than reading accuracy. As a result of the high degree of grapheme–phoneme correspondence in the German writing system, even German dyslexic children show relatively high reading accuracy, but are impaired in reading speed (Wimmer, Landerl, & Frith, 1999; Ziegler, Perry, Ma-Wyatt, Ladner, & Schulte-Körne, 2003). To measure reading speed, the WLLP (Küspert & Schneider, 1998) was used again (maximum reading score = 140). To investigate spelling skills, the *Diagnostischer Rechtschreibtest für 2. Klassen* (DRT 2; Müller, 2004b) was used. In this test, 32 sentences are read to the children. One particular word from each sentence has to be written down (maximum error score = 32). Knowledge of orthographic rules of German is required to write down the words correctly. Thus, this spelling test can be viewed as measuring orthographic spelling ability.

In the first assessment at the beginning of first grade, auditory TOTs could be determined in 163 children (71% of 229 children). Performance of the remaining 66 children did not result in a distribution of responses permitting a sigmoidal fit that yields a plausible threshold (see Method). Visual TOTs were obtained from 196 children (84% of 232 children). In the second assessment near the end of second grade, auditory responses allowing the estimation of thresholds were obtained from 170 children (85% of 199 children), and visual responses from 182 children (89% of 204 children). Auditory TOTs were higher as compared to visual TOTs, and both values decreased in the course of 20 months (see Figure 2).

**Results**

**Auditory and Visual TOTs**

In the first assessment at the beginning of first grade, auditory TOTs could be determined in 163 children (71% of 229 children). Performance of the remaining 66 children did not result in a distribution of responses permitting a sigmoidal fit that yields a plausible threshold (see Method). Visual TOTs were obtained from 196 children (84% of 232 children). In the second assessment near the end of second grade, auditory responses allowing the estimation of thresholds were obtained from 170 children (85% of 199 children), and visual responses from 182 children (89% of 204 children). Auditory TOTs were higher as compared to visual TOTs, and both values decreased in the course of 20 months (see Figure 2).
Data from 102 children with valid thresholds from both modalities and both sessions were used for an omnibus analysis. In Grade 1, this sample had a mean auditory TOT of 131.1 ms (SD = 88.2 ms) and a mean visual TOT of 97.1 ms (SD = 57.7 ms). In Grade 2, the mean auditory TOT was 67.5 ms (SD = 39.9 ms) and the mean visual TOT was 54.5 ms (SD = 33.8 ms). A repeated measures analysis of variance (ANOVA) with the two within-subject factors modality (auditory vs. visual) and time (Grade 1 vs. Grade 2) revealed a main effect of modality, $F(1, 101) = 102.68$, $p < .001$, with auditory TOTs being higher than visual TOTs, and a main effect of time, $F(1, 101) = 102.68$, $p < .001$, with TOTs decreasing from Grade 1 to Grade 2. In addition, the Modality $\times$ Time interaction was significant, $F(1, 101) = 5.61$, $p < .05$. Post hoc paired $t$ tests revealed that the decreases in threshold from Grade 1 to Grade 2 were significant for both the auditory, $t(101) = 8.52$, $p < .001$, and visual, $t(101) = 6.86$, $p < .001$, domains. Visual TOTs were significantly lower than auditory TOTs in both Grade 1, $t(101) = 3.72$, $p < .001$, and Grade 2, $t(101) = 2.66$, $p < .05$. The interaction between modality and time is caused by the fact that in Grade 1, differences between auditory and visual TOTs are more pronounced than in Grade 2.

In both assessments, TOTs in the visual domain were lower as compared to the auditory domain. As auditory transmission times are much faster compared to visual transmission times, we conducted a control experiment to evaluate whether higher TOTs in the auditory system were due to the influence of the explanatory display and the visual cue. We compared our visual and auditory condition with an additional auditory condition: pure auditory stimulation without visual cues. Twenty second-grade children (age range = 7.10–8.9, $M = 8.5$) who did not participate in the main study were recruited from one school. In the control condition the tones were assigned to a cow and a mouse as in the main experiment, but without any visualization. The children were told that the two animals will shout one after another. The task was to indicate verbally which animal was shouting first. Responses were documented by the experimenter by button press. No feedback was given.

Auditory stimulation without visualization yielded even larger TOTs than auditory stimulation with visual cues (Figure 3). A repeated measures ANOVA with the within-subject factor experimental condition (pure auditory vs. auditory with visual cue vs. visual) revealed a main effect of condition, $F(2, 38) = 13.27$, $p < .001$. The auditory task without visualization yielded significantly larger auditory TOTs than the auditory task with visual cues, $t(19) = 4.08$, $p < .001$. Visual TOTs were again lower than auditory TOTs, $t(19) = 2.97$, $p < .01$.

**Correlational Analysis**

To allow direct comparisons between correlation coefficients, only children without missing data were included in the analysis. In this study, 12 measures were collected from each child (4 TOTs, 5 reading and spelling tests, 3 control variables) over a course of nearly 2 years. A total of 71 children had successfully completed all 12 measurements. There were missing data because (a) some children were not available for all psychodiagnostic sessions, (b) some children had problems in peripheral hearing or vision, and (c) valid TOTs could not be estimated for all children. Descriptive statistics for all measures of this sample of 71 children are depicted in Table 1. Bivariate correlations between all measures are shown in Table 2.

Auditory and visual TOTs correlated significantly in Grade 1, but not in Grade 2. Auditory TOTs in Grade 1 were significantly related to auditory TOTs in Grade 2. Likewise, visual TOTs in Grade 1 were related to visual TOTs in Grade 2.

Reading and spelling performance in Grade 1 and Grade 2 were highly correlated: In Grade 1, significant correlations were found between reading speed, reading errors, and spelling errors. In Grade 2, higher reading speed was associated with fewer spelling errors. In addition, reading speed and spelling errors in Grade 1 were related to reading and spelling in...
Grade 2. Reading errors in Grade 1 were related to spelling errors but not to reading speed in Grade 2. The control variables general intelligence, working memory, and attention did not correlate with each other, indicating that they tap different cognitive abilities. None of these variables was related to children's age. The latter is not surprising, though, given that the standard scores of the intelligence and the working memory test are age normed and that the age range between the children is rather small.

In most cases TOTs were not related to general cognitive abilities, except relations between working memory and auditory and visual TOTs in Grade 1. However, several correlations between TOTs and reading and spelling performance were found: The higher the auditory TOT in Grade 1, the higher was the number of reading errors in Grade 1 and reading and spelling errors in Grade 2. By contrast, the visual TOT in Grade 1 was not related to reading and spelling performance in Grades 1 and 2. Auditory TOT in Grade 2 was related to spelling performance in Grade 1. Finally, the higher the visual TOT in Grade 2, the higher was the number of spelling errors in Grade 2.

The four control variables (IQ, working memory, attention, and age) were not related to reading and spelling performance in Grade 1 as well as to reading performance in Grade 2. There were, however, associations between control variables and spelling performance in Grade 2: The smaller the number of spelling errors in Grade 2, the better the child's general cognitive abilities (intelligence, working memory, and attention).

**Regression Analyses**

Two kinds of multiple regression analyses were performed to predict reading and spelling performance in Grade 1 and Grade 2. First, to explore which variable(s) would best predict reading and spelling outcomes, the analyses were computed with

### Table 1
**Descriptive Statistics of the Regression Sample (N = 71)**

<table>
<thead>
<tr>
<th>Measure</th>
<th>M</th>
<th>SD</th>
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<tbody>
<tr>
<td>Temporal order thresholds (TOTs)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Auditory TOT Grade 1 (ms)</td>
<td>127.87</td>
<td>84.77</td>
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<tr>
<td>Visual TOT Grade 1 (ms)</td>
<td>94.66</td>
<td>42.16</td>
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<tr>
<td>Auditory TOT Grade 2 (ms)</td>
<td>66.84</td>
<td>36.70</td>
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<tr>
<td>Visual TOT Grade 2 (ms)</td>
<td>52.81</td>
<td>28.25</td>
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<tr>
<td>Reading and spelling measures</td>
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<td></td>
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<tr>
<td>Reading speed Grade 1 (max. score = 140)</td>
<td>52.94</td>
<td>20.95</td>
</tr>
<tr>
<td>Reading errors Grade 1 (max. error score = 33)</td>
<td>2.07</td>
<td>2.30</td>
</tr>
<tr>
<td>Spelling errors Grade 1 (max. error score = 30)</td>
<td>3.54</td>
<td>3.39</td>
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<tr>
<td>Reading speed Grade 2 (max. score = 140)</td>
<td>84.80</td>
<td>23.32</td>
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<tr>
<td>Spelling errors Grade 2 (max. error score = 32)</td>
<td>12.07</td>
<td>6.38</td>
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<tr>
<td>Control variables</td>
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<tr>
<td>IQ (M = 100, SD = 15)</td>
<td>113.87</td>
<td>12.92</td>
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<tr>
<td>Working memory (max. standard score = 19)</td>
<td>10.08</td>
<td>2.27</td>
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<tr>
<td>Attention (max. score = 45)</td>
<td>23.38</td>
<td>4.31</td>
</tr>
<tr>
<td>Age at first data point (in months)</td>
<td>79.51</td>
<td>4.07</td>
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</tbody>
</table>

Note. *TOT = temporal order threshold.

### Table 2
**Bivariate Correlations Between All Measures (N = 71)**

<table>
<thead>
<tr>
<th>Measure</th>
<th>1</th>
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<th>3</th>
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<th>12</th>
<th>13</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. Auditory TOT 1</td>
<td>1</td>
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<tr>
<td>2. Visual TOT 1</td>
<td>.39**</td>
<td>1</td>
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<tr>
<td>3. Auditory TOT 2</td>
<td>.50**</td>
<td>.22</td>
<td>1</td>
<td></td>
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<td>4. Visual TOT 2</td>
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<td>.26*</td>
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<td>5. Reading speed 1</td>
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<td>-.13</td>
<td>-.12</td>
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<td>.28*</td>
<td>.07</td>
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<td>.21</td>
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<td>7. Spelling errors 1</td>
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<td>.25*</td>
<td>.10</td>
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<td>-.06</td>
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<td>.20</td>
<td>.26*</td>
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<td>.39**</td>
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Note. TOT = temporal order threshold. Numbers refer to school grades: 1 = Grade 1, 2 = Grade 2.

*p < .05. **p < .01.
a forward procedure, in which all variables were entered simultaneously. Second, to learn something about the unique contribution of rapid temporal processing to the development of reading and spelling after controlling for the effect of other cognitive variables, a stepwise procedure was used in which the variance explained by the control variables was taken into account first before the predictive value of rapid temporal processing abilities was assessed. To allow direct comparisons between results from different analyses, the same participants were included in all regression analyses, that is, only those children without missing data (N = 71). Due to the rather small sample size, results are not reported separately for males versus females.

**Exploratory Regression Analyses**

To predict reading and spelling performance at the end of Grade 1, auditory and visual TOTs at the beginning of Grade 1 as well as the four control variables (IQ, working memory, attention, and age) were used as predictors. None of these variables explained a significant amount of variance in reading speed. The only significant predictor for reading accuracy was auditory TOT, $t(70) = 2.37$, $p < .05$; standardized $\beta = .28$, which explained 6.2% of the variance (adjusted $R^2$). The only significant predictor of spelling accuracy was again auditory TOT, $t(70) = 2.38$, $p < .05$; standardized $\beta = .28$, again explaining 6.2% of the variance.

To predict reading and spelling performance at the end of Grade 2, all four TOJ measures (auditory and visual TOT Grade 1, auditory and visual TOT Grade 2) and the four control variables (IQ, working memory, attention, and age) were used as predictors. None of the predictors explained a significant amount of variance in reading speed. For spelling accuracy two regression models were significant. In Model 1, auditory TOT in Grade 1 significantly predicted spelling accuracy, $t(70) = 3.01$, $p < .01$; standardized $\beta = .34$. Using this model, auditory TOT in Grade 1 explained 10.4% of the variance in spelling accuracy in Grade 2. In Model 2, a combination of auditory TOT in Grade 1, $t(70) = 3.17$, $p < .01$; standardized $\beta = .34$, and attention, $t(70) = 2.75$, $p < .01$; standardized $\beta = .30$, explained 18.1% of the variance in spelling accuracy in Grade 2.

**Stepwise Regression Analyses**

To predict reading and spelling performance at the end of Grade 1, a stepwise regression procedure was chosen in which the four control variables (IQ, working memory, attention, and age) were entered in the first block, and the variables of interest (auditory and visual TOTs at the beginning of Grade 1) were entered in the second block. The results of all three regression analyses (using reading speed, reading accuracy, and spelling accuracy as criterion variables) were exactly the same as in the exploratory regression analyses. The reason for this is that all four control variables are only weakly correlated with the reading and spelling variables in Grade 1 (see Table 2), so that they do not explain a significant amount of variance in reading and spelling.

To predict reading and spelling performance at the end of Grade 2, a stepwise regression procedure was chosen in which the four control variables (IQ, working memory, attention, and age) were entered in the first block and the predictor variables of interest (auditory and visual TOTs at the beginning of Grade 1 and near the end of Grade 2) were entered in the second block. None of the variables explained a significant amount of variance in reading speed in Grade 2. The four predictor variables attention, working memory, age, and auditory TOT in Grade 1 explained, however, a total of 21.9% of the variance in spelling accuracy in Grade 2. The strongest predictor was attention, explaining 7.4% of the variance in spelling accuracy, $t(70) = 2.57$, $p < .05$; standardized $\beta = .30$. Working memory explained 6.4% of the variance in spelling, $t(70) = -2.46$, $p < .05$; standardized $\beta = -.27$, and age explained 4.3%, $t(70) = -2.16$, $p < .05$; standardized $\beta = -.24$. The weakest yet still significant predictor of spelling accuracy in Grade 2 was auditory TOT in Grade 1, explaining an additional 3.8% of the variance, $t(70) = 2.06$, $p < .05$; standardized $\beta = .24$.

**Discussion**

We conducted a longitudinal study with primary school children to investigate relations between rapid temporal processing and reading and spelling development in Grades 1 and 2. Rapid auditory and visual processing abilities were assessed twice over a period of 20 months (beginning of Grade 1 vs. near the end of Grade 2) using adaptive psychophysical tasks implemented as computer games. To control for the influence of general cognitive abilities on temporal processing and on the development of literacy, we assessed general intelligence, working memory, and attention.
Development of Rapid Temporal Processing in First and Second Grades

The results of our auditory and visual temporal processing tasks show that it is, in principle, possible to use adaptive psychophysical methods to measure rapid temporal processing abilities already in first graders (aged about 6 years). At this data point, auditory TOTs could be determined for more than 70% of the sample and visual TOTs could be generated even for more than 80%. On the other hand, this rate also suggests that children of this age might still have trouble performing this kind of tasks properly, which confirms earlier findings (Berwanger, Wittmann, von Steinbüchel, & von Suchodoletz, 2004; Nickisch, 1999). As general cognitive variables (intelligence, working memory, and attention) were also assessed, we were able to check whether general cognitive characteristics might explain children’s failure to perform the TOJ tasks in Grade 1. We found that children for whom thresholds could not be determined (auditory TOT: n = 66; visual TOT: n = 36) tended to have a lower general intelligence, a shorter working memory span, and weaker attentional abilities than their peers (all ps < .07). This implies that the findings concerning auditory and visual TOTs in Grade 1 might not be generalizable to the whole population, but might only refer to children with a more favorable cognitive development.

In this study, auditory TOTs were larger than visual TOTs both in Grade 1 and in Grade 2. In both modalities, TOTs decreased from Grade 1 to Grade 2. The finding of larger auditory than visual TOTs is puzzling, as neural transmission times from the sensory organ to the cortex are much faster in the auditory domain compared to the visual domain. Indeed, Landerl and Willburger (2010) report larger visual than auditory TOTs for a sample of second-, third- and fourth-grade children. These authors used, however, standard paradigms of auditory and visual TOJ in their study, whereas in our study the TOJ tasks were disguised as computer games. One explanation of the larger auditory than visual TOTs in this study could be that the use of visual information as cues in the auditory task might serve as an attention capture, leading to a slowing down of auditory processing. We tested this hypothesis with a control experiment that showed that auditory TOTs even increased when visual cues were removed from the experimental setting. Thus, the visual cues employed in the original task seem to have a facilitating effect. Note, however, that TOTs may also be influenced by procedure-related factors such as the spatial location of the stimuli, the features by which stimuli differ, or the stimulus durations (Szelag, Kanabus, Kolodziejczyk, Kowalska, & Szuchnik, 2004).

It has been shown that in adults TOTs typically range between 20 and 60 ms and have similar values in different sensory modalities (Szelag et al., 2004). To evaluate if, with the present adaptive procedure, adults’ TOTs lie within this threshold range, a sample of 17 adults performed the same auditory and visual TOJ tasks as the children in the main experiment. In adults, both auditory and visual TOTs were in the expected threshold range (auditory TOT: $M = 55.2$; visual TOT: $M = 40.4$) and differences between auditory and visual TOTs were not significant, $t(16) = 1.6$, $p = .12$. Relating children’s mean auditory TOTs to those of the adults, our results show that first-grade children’s auditory TOT is 2.4 times higher than that of adults, and 20 months later it is 1.2 times higher (first graders: 131 ms; second graders: 67 ms; and adults: 55 ms). The finding that young children’s auditory TOTs are much higher than those of adults is corroborated by cross-sectional studies (Berwanger et al., 2004; Nickisch, 1999). Also in the visual modality, the TOT of first graders is 2.4 times larger than that of adults, and 20 months later it is 1.4 times larger (first graders: 97 ms; second graders: 54 ms; and adults: 40 ms). Thus, temporal resolution of first graders is inferior to that of adults in both the visual and auditory domains, gradually improves over time, but has not yet reached an adult level at the end of Grade 2. Interestingly, the differences between adult and child TOTs and the relative improvement of temporal resolution over time were analogous in both modalities. This might indicate that auditory and visual TOTs do not only have a comparable endpoint in adulthood but also show the same developmental trajectories in childhood.

Results from the correlational analyses revealed that in both modalities, in the auditory as well as in the visual, TOTs in Grade 1 and Grade 2 are related. This indicates that although temporal resolution in both modalities improves with age, the relative placement of a child’s TOT within the cohort remains rather stable. It has to be kept in mind, however, that auditory and visual TOTs in Grade 1 were also related to children’s working memory abilities. This suggests that working memory ability mediates children’s performance in temporal tasks, at least in younger children. On the contrary, general intelligence and attention were not related to auditory and visual TOTs. The lack
of relations between auditory TOTs and attention was surprising as a study on auditory processing in children by Moore, Ferguson, Edmondson-Jones, Ratib, and Riley (2010) has shown that poor performance on auditory tasks is attributable to the attentional demands of the task. Altogether, in our study there is not much support for relations between general cognitive abilities and temporal processing abilities in this age group, which is at odds with the results by Hood and Conlon (2004) but corroborates former findings of weak relations between auditory processing and general cognitive variables such as intelligence and working memory (Moore et al., 2010). Our findings, therefore, reflect temporal processing abilities, not general cognitive abilities.

Do Rapid Temporal Processing Abilities Predict Reading and Spelling Outcomes in Grades 1 and 2?

Rapid auditory processing at the beginning of Grade 1 was a predictor for reading and spelling outcomes at the end of Grades 1 and 2. Grade 1 rapid auditory processing accounted for small but significant amounts of variance in reading accuracy in Grade 1, and in spelling accuracy in Grades 1 and 2. Interestingly, rapid auditory processing abilities were a better predictor of reading and spelling at the end of Grade 1 than general cognitive variables like intelligence, working memory, and attention. This result is in line with longitudinal results from Benasich and colleagues (e.g., Benasich & Tallal, 2002; Choudhury, Leppänen, Leevers, & Benasich, 2007) who showed that infant rapid auditory processing skills are predictive of later language abilities and that they predict language better than more general cognitive measures do. Rapid visual processing, however, made no independent contribution to the prediction of reading and spelling abilities. None of the variables tested accounted for a significant proportion of variance in reading speed at the end of Grades 1 and 2.

The finding that early rapid auditory processing abilities predict reading accuracy in Grade 1 corroborates findings from a study by Hood and Conlon (2004). In that study, rapid auditory processing measures did, however, also predict reading speed, which was not found in this study. For temporal auditory processing to predict reading accuracy but not reading speed seems counterintuitive, as reading speed is viewed as the main indicator of reading abilities in transparent orthographies like German (see Method). Moreover, reading speed and reading errors in Grade 1 were moderately correlated. Regarding the latter point, it could be argued that reading accuracy can be viewed as a prerequisite for reading fluency: As reading fluency requires rehearsal and automatization, reading can only become fluent when it is accurate (see also Pennala et al., 2010). Regarding the relations between rapid auditory processing abilities and reading speed, we suggest that the difference between Hood and Conlon’s (2004) and our results might stem from the fact that in German, as opposed to English, reading fluency is influenced more by naming speed than by phonological awareness (Wimmer, Mayringer, & Landerl, 2000). As rapid auditory processing abilities seem to be more strongly related to phonological awareness than to naming speed (see Share et al., 2002), the relation between rapid auditory processing and reading speed is expected to be stronger in English than in German. However, none of the two studies investigated this relation explicitly. Longitudinal studies are needed that address the question how exactly rapid temporal processing abilities influence phonological processing abilities. Note that Boets, Wouters, van Wieringen, de Smedt, and Ghesquière (2008) used this kind of approach, but with dynamic and not rapid auditory and visual processing.

This study is the first longitudinal study showing that rapid auditory processing is a predictor of spelling ability in children. How can the connection between rapid auditory processing and spelling be explained? Efficient rapid auditory processing is relevant for phoneme perception, as acoustic cues differentiating between phonemes may lie in time windows as short as 20–40 ms (Bishop, 1997; Tallal, 2000). Thus, the better children’s rapid temporal processing abilities, the better their phoneme perception. The quality of children’s phoneme perception, in turn, determines the quality of the long-term memory representations of these phonemes and has an impact on children’s ability to learn grapheme–phoneme mappings (Manis et al., 1997). Finally, the proficiency of converting phonemes into graphemes might be of relevance for early spelling abilities, especially in transparent orthographies like German. Indeed, although German exhibits a much higher regularity in the direction of graphemes to phonemes than in the direction of phonemes to graphemes (see Wimmer & Mayringer, 2002), it is very common in Germany to base early spelling instruction on phoneme–grapheme mappings (see Füssenschich & Löfler, 2005). Thus, it can be expected that German children use an alphabetic spelling strategy (Frith, 1986) in the early school years. Indeed,
Wimmer and Hummer (1990) found that German-speaking first graders rely on an alphabetic strategy for both reading and spelling. Thus, the reported impact of early rapid auditory processing abilities on spelling in Grades 1 and 2 might be explained by its effect on phoneme perception and the learning of grapheme–phoneme mappings, which in turn influence spelling accuracy.

The longitudinal approach concerning the measurement of rapid temporal processing abilities allowed determining whether earlier (Grade 1) or later (Grade 2) temporal processing abilities are more relevant for the development of literacy. It turned out that rapid auditory processing ability at the beginning of Grade 1 was a better predictor than that of Grade 2 for spelling abilities at the end of Grade 2. Thus, early rapid auditory processing ability preceding spelling instruction served as the best explaining factor for spelling ability 2 years later. This underpins the argument that auditory processing abilities are indeed causally related to the development of literacy and underscores the importance of longitudinal designs.

That the effect of rapid auditory processing ability on literacy decreases over time is also relevant for the interpretation of findings on rapid auditory processing deficits in dyslexia: The rapid auditory processing deficit as such might diminish over time, but its detrimental effects on reading and spelling ability might remain, as it has disturbed the early literacy development. In animal modeling studies, lesions-producing microgyria much like those seen in adult dyslexic brains led to rapid auditory processing deficits in juvenile rats on simpler tasks, whereas more complex tasks were needed to elicit rapid auditory processing deficits in disrupted adult rats (Peiffer, Friedman, Rosen, & Fitch, 2004). These findings are consistent with the idea that individual differences or impairments in these underlying skills may be easier to characterize at younger ages, yet long-term effects of disruption to these early processes may be evident later using more difficult tasks (e.g., language), and particularly tasks that developmentally build upon those more basic early skills. Thus, if a cross-sectional study does not find rapid auditory processing deficits in dyslexia, this result can, strictly speaking, not be taken as evidence against the rapid auditory processing theory of dyslexia.

Relations between general cognitive abilities (general intelligence, working memory, and attention) and literacy were only found for spelling in Grade 2. In stepwise multiple regression analyses, attention as well as working memory explained significant amounts of variance in spelling in this grade. As was explained above, German children use an alphabetic spelling strategy for early spelling. In later phases of spelling development, in addition, children have to acquire orthographic rules and have to rely on holistic long-term representations of irregular words because phoneme–grapheme relations are often not regular in German (only 47% of German monosyllabic words have regular phoneme–grapheme mappings; Wimmer & Mayringer, 2002). This later developed spelling strategy seems to depend more on general cognitive abilities.

That some studies found a relation between general cognitive abilities and literacy, whereas we, altogether, did not, may be due to methodological differences, for instance, in sample size: N = 71 in this study, as compared to N = 98 in Alloway and Alloway (2010) and even N = 350 in Talcott et al. (2002). Indeed, rerunning the simple correlation analyses, this time including all available data sets (N between 122 and 236) revealed that in this larger sample intelligence and working memory are related to reading and spelling measures. In addition, the regression sample, which completed all 12 measurements over a course of 2 years, differed from children with missing data with respect to intelligence and working memory (but not attention) as well as reading and spelling abilities (all ps < .05). However, rerunning the exploratory regression analyses using all available data sets (N between 85 and 123) revealed, in principle, the same results as with the N = 71 sample, and rapid auditory processing still turned out to be the most important predictor of literacy abilities.

One might object that the effect of rapid auditory processing should not be overestimated, as it explains only between about 4% and 10% of variability in literacy development. However, taking into account the number of cognitive processes that influence literacy development (see Vellutino, Fletcher, Snowling, & Scanlon, 2004), notwithstanding environmental factors, it seems remarkable, though, that a single basic auditory processing ability measured in an unselected sample of primary school children turns out a predictor of literacy development, and, concerning reading and spelling accuracy in Grade 1, even a more important one than general cognitive abilities. Still, the question remains if the influence of rapid auditory processing abilities on literacy development is independent from that of other cognitive variables known to
influence reading and spelling development, such as phonological processing abilities and rapid naming. In fact, a recent cross-sectional study by Malenfant et al. (2012) showed that the effect of rapid temporal processing abilities on reading comprehension is mediated by phonological awareness. Future studies should address this issue using longitudinal designs.

Rapid visual processing made no unique contribution to the prediction of reading and spelling skills in Grades 1 and 2. Thus, rapid auditory processing seems to be of greater importance for literacy development than rapid visual processing. The correlations show, however, that the visual TOT near the end of Grade 2 is related to Grade 2 spelling, but the visual TOT at the beginning of Grade 1 is not. Thus, rapid visual processing abilities might be more relevant in later phases of literacy development than in the earlier phases. This is consistent with the results of the longitudinal study by Hood and Conlon (2004), who found that earlier visual TOJ abilities were not related to reading development, but later visual TOJ abilities were. The pattern of relations in the present study between temporal processing abilities and literacy development suggests that rapid auditory processing is especially relevant for early phases of literacy development, in which phonemes in spoken language have to be accurately perceived and discriminated from each other to learn phoneme–grapheme mappings and to establish an alphabetic reading and spelling strategy. In later phases of literacy development, the influence of rapid auditory processing might decline, as reading and spelling strategies do not focus any more on these basic auditory processes. By contrast, rapid visual processing may not be that relevant for early phases of literacy development, but might gain in processing may not be that relevant for early phases of auditory processes. By contrast, rapid visual processing abilities might not be that relevant in languages with more consistent orthographies, but might contribute to developmental dyslexia in languages with less consistent orthographies, but might not be that relevant in languages with more consistent orthographies (Papadopoulos et al., 2012). Thus, it seems critical for future research to determine the unique impact of rapid versus dynamic temporal processing abilities on the development of literacy and to explore further its dependency on language transparency.

Conclusions

This study is the first measuring both auditory and visual TOTs longitudinally in a large sample of primary school children. TOTs were assessed twice, that is, at the beginning of Grade 1 and 20 months later near the end of Grade 2, using an adaptive staircase wrapped in an age-appropriate computer game. In both the visual and auditory modality, children’s TOTs were much larger than those of adults, decreased from Grade 1 to Grade 2, but did not yet reach an adult level at the end of Grade 2. Although the absolute heights of auditory and visual TOTs varied considerably, parallel developmental trajectories were found for both modalities.

Rapid auditory processing at the beginning of Grade 1 was a better predictor for reading and spelling abilities at the end of Grade 1 than general cognitive abilities (intelligence, working memory, and attention) and did also significantly predict spelling accuracy in Grade 2. Interestingly, rapid
auditory processing abilities in Grade 1 predicted spelling abilities in Grade 2 better than those in Grade 2. This finding underscores that rapid auditory processing abilities are a cause rather than a mere correlate of literacy development. Rapid visual processing abilities did not independently contribute to reading and spelling outcomes. Correlational findings indicated, however, that the importance of rapid visual processing for the development of spelling increases over time. This pattern of results suggests that rapid auditory processing is of special importance for early literacy development, whereas rapid visual processing might be more relevant for the later literacy development.

References


