Modelling relations between sensory processing, speech perception, orthographic and phonological ability, and literacy achievement

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Abstract

The general magnocellular theory postulates that dyslexia is the consequence of a multimodal deficit in the processing of transient and dynamic stimuli. In the auditory modality, this deficit has been hypothesized to interfere with accurate speech perception, and subsequently disrupt the development of phonological and later reading and spelling skills. In the visual modality, an analogous problem might interfere with literacy development by affecting orthographic skills. In this prospective longitudinal study, we tested dynamic auditory and visual processing, speech-in-noise perception, phonological ability and orthographic ability in 62 five-year-old preschool children. Predictive relations towards first grade reading and spelling measures were explored and the validity of the global magnocellular model was evaluated using causal path analysis. In particular, we demonstrated that dynamic auditory processing was related to speech perception, which itself was related to phonological awareness. Similarly, dynamic visual processing was related to orthographic ability. Subsequently, phonological awareness, orthographic ability and verbal short-term memory were unique predictors of reading and spelling development.

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1. Introduction

Developmental dyslexia is a specific failure to acquire reading and spelling skills despite adequate intelligence and instruction, affecting around 5–10% of children and adults. The aetiology of these unexpected literacy problems remains unclear, but deficits in the cognitive-linguistic domain, the auditory domain and the visual domain have been proposed (Vellutino, Fletcher, Snowling, & Scanlon, 2004). A well-established theory contends that individuals with dyslexia have a phonological deficit, which is causal to their reading and spelling difficulty (Snowling, 2000). Phonological deficits have been demonstrated in phonological awareness, retrieval of phonological codes from long-term memory (rapid automatic naming) and verbal short-term memory (Wagner & Torgesen, 1987). Research on the underlying neurological dysfunction of dyslexia suggests that this phonological deficit might result from a more basic deficit in auditory temporal processing. Subjects with dyslexia tend to have problems processing short, rapidly presented and dynamic changing acoustic stimuli (e.g., Farmer & Klein, 1995; McArthur & Bishop, 2001; Menell, McAnally, & Stein, 1999; Talcott, Hansen, Assoku, & Stein, 2000; Talcott & Witton, 2002; Tallal, 1980; Van Ingelghem et al., 2005). Auditory temporal processing problems have been hypothesized to interfere with the accurate detection of the acoustical changes in speech. The resulting speech perception problem might subsequently disrupt the normal development of the phonological system and lead to problems learning to read and spell.
(Talcott & Witton, 2002; Tallal, 1980; Wright et al., 1997). However, the evidence of an auditory temporal processing deficit is not yet unequivocal (for a critical review see Rosen, 2003).

Alternatively, some subjects with dyslexia seem to present a specific deficit in magnocellular visual processing (Stein & Walsh, 1997). This deficit was demonstrated using stimuli that assess the peripheral visual system (e.g., contrast sensitivity and flicker sensitivity paradigms; for a review see Lovegrove, 1996, but see Skottun, 2000 for a critical revision) as well as higher level magnocellular functioning such as coherent motion detection (e.g., Raymond & Sorensen, 1998; Talcott, Hansen, Assoku, & Stein, 2000a; Talcott & Witton, 2002; Wilmer, Richardson, Chen, & Stein, 2004; Witton et al., 1998). As in the auditory line of research, not all visual studies were able to demonstrate the magnocellular deficit in dyslexia (Amitay, Ben-Yehudah, Banai, & Ahissar, 2002; Kronbichler, Hutzler, & Wimmer, 2002; Ramus et al., 2003). There is still much speculation about the specific mechanism by which a visual magnocellular dysfunction may limit normal literacy development. The answer might probably lie in the anatomical connections from the magnocellular pathway to the posterior parietal cortex, which is involved in normal eye movement control, visuospatial attention, visual search, letter position encoding and peripheral vision — factors that are obviously involved in the development of orthographic skills and subsequent reading and spelling skills (Stein, 2001; Stein & Talcott, 1999; Stein & Walsh, 1997).

The general magnocellular theory integrates the cognitive-linguistic, the auditory and the visual research tradition. This comprehensive theory assumes that dyslexia is due to a multimodal sensory deficit in the processing of transient and dynamic stimuli (e.g., Stein & Talcott, 1999; Talcott & Witton, 2002; Talcott et al., 2000b). It postulates that both the auditory and the visual processing deficits might arise from one common biological cause, i.e., a deficit in the neural pathways involved in the fast transmission and processing of sensory information (Stein, 2001; Stein & Walsh, 1997). Validation of these neurobiological assumptions remains, however, a controversial issue (e.g., Ramus, 2003). A further critical issue challenging the general magnocellular theory deals with the difficulty to demonstrate the hypothesized sensory deficits in individual subjects with dyslexia (e.g., Boets, Wouters, Van Wieringen, & Ghesquière, 2007; Ramus et al., 2003). In spite of this, the general magnocellular theory provides a valuable integrative theoretical framework to study a wide range of variables that might affect literacy development.

According to the general magnocellular theory, two predictions can be formulated: (1) subjects with dyslexia are hypothesized to demonstrate auditory and visual temporal processing deficits, speech perception problems and orthographic/phonological problems, and (2) significant relations between auditory temporal processing, speech perception, phonological ability and literacy achievement on the one hand, and between visual temporal processing, orthographic ability and literacy on the other hand, should be observed. In a previous study of our longitudinal research program (Boets, 2006; Boets, De Smidt, Wouters, Lemay, & Ghesquière, 2007; Boets, Wouters et al., 2007), we reported that children with dyslexia at the group level presented significant preschool deficits in auditory frequency modulation detection, visual coherent motion detection, speech-in-noise perception, phonological awareness, rapid automatic naming and letter knowledge. This indicates that the hypothesized deficits are already present at a preschool age and do precede the literacy problem. The present paper further elaborates on the data of these same children and focuses on the interrelations as proposed in the second prediction of the general magnocellular theory.

Several studies have reported correlations between (a) auditory processing and phonological or reading abilities (e.g., Amitay, Ahissar, & Nelken, 2002; Van Ingelghem et al., 2005), (b) visual magnocellular processing and orthographic or reading skills (e.g., Cornelissen et al., 1998; Demb, Boynton, & Heeger, 1997), and (c) speech perception and phonological or reading abilities (e.g., Mayo, Scobbie, Hewlett, & Waters, 2003; McBride-Chang, 1996; Schulte-Körne, Deimel, Bartling, & Remschmidt, 1999; Watson & Miller, 1993). The latter three studies also suggested that this association between speech perception and reading ability might be mediated by phonological processes.

The reported studies present, however, two limitations. First, most of these studies did either assess auditory or visual temporal processing capacities, but did not consider them simultaneously to explain variation in literacy ability. An exception is the study by Talcott et al. (2000), which demonstrated an exclusive relation between visual magnocellular processing and orthographic skills, and between auditory processing and phonological ability. However, in similar integrative studies, Talcott et al. (2002), White et al. (2006) and Ramus et al. (2003) could only partially replicate these findings.

Second, the reported cross-sectional studies generally investigated adult and school-aged subjects. Therefore, they do not allow conclusions regarding the directionality of the studied relations. For example, these studies cannot discern whether the sensory deficits associated with dyslexia are a cause, a consequence or a non-causally related marker of the literacy problem. Moreover, the few studies that did assess auditory (Heath & Hogben, 2004; Share, Jorm, MacLean, & Matthews, 2002) and auditory and visual (Hood & Conlon, 2004) temporal order judgement tasks in preschoolers, yielded mixed results in relating sensory thresholds to later literacy development.

The present study tries to deal with these issues by examining auditory and visual temporal processing skills, speech perception, orthographic and phonological ability in preschool children, that were studied from one year before the onset of formal reading instruction (last year of kinder-
garten) until one year into reading instruction (first grade). The aim of this study was twofold. First, we wanted to investigate the entire general magnocellular model, comprising visual and auditory measures as well as intermediate measures (i.e., speech perception and phonological and orthographic ability). Second, by relating preschool measures (assessed before formal reading instruction) to literacy achievement at the end of first grade, we wanted to gain additional insight into the directionality of these relations. To accomplish this, causal path analysis techniques, adjusted for small sample sizes, were used.

Based upon the general magnocellular theory and the traditional phonological theory, we constructed and tested the model depicted in Fig. 1. With regard to the auditory pathway, this model assumes that dynamic auditory processing determines speech perception, which on its turn determines phonological ability. Although we mainly expect an influence of speech perception upon phonological awareness, we also allow rapid automatic naming and verbal short-term memory to be determined by speech perception (McBride-Chang, 1996). In addition, all three phonological subskills are assumed to be mutually correlated (e.g., Wagner & Torgesen, 1987) and are hypothesized to act upon literacy development. With regard to the visual pathway, the model assumes that dynamic visual processing determines orthographic ability, which in its turn determines reading and writing development. Furthermore, the measures for auditory and visual processing are allowed to correlate, as they both depend on dynamic sensory processing (Talcott & Witton, 2002).

2. Method

2.1. Participants

Participants were 62 children (36 boys/26 girls) that were followed up in the context of an ongoing longitudinal research project (see Boets, Wouters, van Wieringen, & Ghesquiere, 2006a). All children were native Dutch speakers without a history of brain damage, psychiatric disorder, hearing loss or visual problems. At the time of testing, they did not present any gross deficiencies in visual acuity (Landolt-C single optotypes Snellen acuity >0.85) and audiology (audiometric pure-tone average <25 dB HL). Half of the children were selected because of a family history of dyslexia (the high-risk group), the other half were matched control children (the low-risk group). Both groups of children were individually matched on (1) school, (2) gender, (3) age, (4) non-verbal intelligence and (5) parental educational level. There were no group differences on any of the matching criteria. Assessment of reading and spelling achievement at the end of first grade indicated that nine children of the high-risk group (29%) and three of the low-risk group (9%) presented significant literacy problems (Boets, Wouters et al. 2007). Table 1 displays descriptive statistics for the total group of subjects. Children scored slightly above population average on Raven Coloured Progressive Matrices (Raven, Court, & Raven, 1984), a collective non-verbal intelligence test measuring spatial reasoning. Mean age at the first time of data collection was 5 years and 4 months (SD = 3 months).

Fig. 1. The original structural model tested in the path analysis.
2.2. Materials

2.2.1. Phonological tests

The three traditional domains of phonological skills (Wagner & Torgesen, 1987) were assessed: (1) phonological awareness was measured by a rhyme task and three sound identity tasks (first-sound, end-sound, rhyme); (2) verbal short-term memory was measured by a digit span test and a non-word repetition test; (3) rapid automatic naming was assessed with a color and an object naming task. A detailed description of the phonological tasks can be found in Boets et al. (2006a).

2.2.2. Productive letter knowledge

The 16 most frequently used letters in Dutch books were presented on a card and the child had to name each of these letters.

2.2.3. Dynamic auditory processing

Dynamic auditory processing was assessed with a frequency modulation (FM) detection task. In this task, children were required to detect a 2 Hz sinusoidal frequency modulation of a 1 kHz carrier tone with varying modulation depth. Threshold was defined as the minimum depth of frequency deviation required to detect the modulation. Thresholds were estimated using a three-interval forced-choice oddity paradigm embedded within an interactive computer game with animation movies (Laneau, Boets, Moonen, van Wieringen, & Wouters, 2005). The depth of modulation was adjusted adaptively using a two-down, one-up rule, which targeted the threshold corresponding to 70.7 percent correct responses. After a short period of practice, three thresholds were determined for every subject. A more detailed description of the stimuli, procedure and equipment can be found in Boets et al. (2006a).

2.2.4. Dynamic visual processing

A coherent motion (CM) detection task was used to assess children’s visual dynamic processing. In this task, children were sitting in front of a computer screen, which displayed two rectangular patches, each containing 1103 randomly moving high luminance white dots on a black background. The target patch was segregated into three horizontal strips. In the middle strip a variable proportion of dots were moving coherently in horizontal direction, reversing direction every 330 ms; all other dots were moving randomly. Children had to identify the patch which contained the strip of coherently moving dots. Threshold was defined as the smallest proportion of coherently moving dots required for detection, and was estimated using a two-down, one-up adaptive staircase procedure. The experiment was integrated within a computer game with animation movies and an extensive reinforcement system to make it attractive and applicable for very young children (see Boets, Wouters, van Wieringen, & Ghesquière, 2006b).

### Table 1

<table>
<thead>
<tr>
<th>Measure</th>
<th>Maximum⁴</th>
<th>Mean</th>
<th>SD</th>
<th>Range</th>
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</thead>
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<tr>
<td><strong>Preschool measures</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Age (months)</td>
<td>—</td>
<td>64.1</td>
<td>2.9</td>
<td>59–69</td>
</tr>
<tr>
<td>Non-verbal IQ</td>
<td>—</td>
<td>108.6</td>
<td>13.9</td>
<td>74–134</td>
</tr>
<tr>
<td>Simple rhyme</td>
<td>8</td>
<td>6.7</td>
<td>2.2</td>
<td>0–8</td>
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<tr>
<td>Rhyme identity</td>
<td>12</td>
<td>9.3</td>
<td>2.4</td>
<td>2–12</td>
</tr>
<tr>
<td>First-sound identity</td>
<td>10</td>
<td>5.1</td>
<td>2.3</td>
<td>1–10</td>
</tr>
<tr>
<td>End-sound identity</td>
<td>10</td>
<td>5.2</td>
<td>2.4</td>
<td>0–10</td>
</tr>
<tr>
<td>Colour naming (items/s)</td>
<td>—</td>
<td>0.66</td>
<td>0.15</td>
<td>0.42–1.09</td>
</tr>
<tr>
<td>Picture naming (items/s)</td>
<td>—</td>
<td>0.66</td>
<td>0.15</td>
<td>0.36–1.14</td>
</tr>
<tr>
<td>Digit span</td>
<td>21</td>
<td>7.0</td>
<td>1.6</td>
<td>4–10</td>
</tr>
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<td>Non-word repetition test</td>
<td>48</td>
<td>18.6</td>
<td>6.5</td>
<td>3–32</td>
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<tr>
<td>Letter knowledge</td>
<td>16</td>
<td>2.5</td>
<td>3.4</td>
<td>0–13</td>
</tr>
<tr>
<td>Frequency modulation detection (Hz)⁵</td>
<td>—</td>
<td>7.7</td>
<td>4.3</td>
<td>1.9–19.9</td>
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<tr>
<td>Coherent motion detection (% coherence)⁵</td>
<td>—</td>
<td>0.19</td>
<td>0.10</td>
<td>0.07–0.74</td>
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<tr>
<td>Speech-in-noise perception –4 dB SNR (% correct)</td>
<td>1.00</td>
<td>0.47</td>
<td>0.13</td>
<td>0.20–1.00</td>
</tr>
<tr>
<td>Speech-in-noise perception –7 dB SNR (% correct)</td>
<td>1.00</td>
<td>0.24</td>
<td>0.11</td>
<td>0.00–0.50</td>
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<tr>
<td><strong>First-grade literacy measures</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Real-word reading</td>
<td>116</td>
<td>18.7</td>
<td>9.1</td>
<td>2–51</td>
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<tr>
<td>Pseudo-word reading</td>
<td>116</td>
<td>19.3</td>
<td>9.4</td>
<td>1–40</td>
</tr>
<tr>
<td>Real-word reading accuracy</td>
<td>40</td>
<td>25.3</td>
<td>11.9</td>
<td>1–39</td>
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<tr>
<td>Real-word reading speed</td>
<td>150</td>
<td>69.1</td>
<td>33.9</td>
<td>9–148</td>
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<tr>
<td>Pseudo-word reading accuracy</td>
<td>40</td>
<td>17.4</td>
<td>11.2</td>
<td>0–37</td>
</tr>
<tr>
<td>Pseudo-word reading speed</td>
<td>150</td>
<td>47.0</td>
<td>25.1</td>
<td>4–139</td>
</tr>
<tr>
<td>Spelling</td>
<td>60</td>
<td>49.2</td>
<td>10.2</td>
<td>6–60</td>
</tr>
<tr>
<td>Pseudohomophone test</td>
<td>40</td>
<td>29.1</td>
<td>4.5</td>
<td>20–39</td>
</tr>
</tbody>
</table>

⁴ This refers to the highest possible score on a test.
⁵ For frequency modulation and coherent motion detection, the average of the best and second best threshold is displayed.
After a short period of practice, four thresholds were determined for every subject.

2.2.5. Speech perception

Speech perception was evaluated with a standardized speech-in-noise perception task, developed for use in 5–6 years olds (the Göttingerlist II, recorded by Wouters, Damman, & Bosman, 1994; see also Boets, Ghesquière, van Wieringen, & Wouters, 2007; van Wieringen & Wouters, 2005). In this task, 40 high-frequency monosyllable words were presented monaurally together with a continuous stationary speech noise. Words were presented at −4 and −7 dB signal-to-noise ratio (SNR). Children were asked to repeat the words as accurately as possible (for details, see Boets, Ghesquière et al. 2007).

2.2.6. Literacy measures

2.2.6.1. Single word reading. The One-Minute Real-Word Reading test (Brus & Voeten, 1973) and the Pseudo-Word Reading test (van den Bos, Spelberg, Scheepstra, & De Vries, 1994) were administered. To disentangle reading accuracy and reading speed, four additional reading tests, comprising the Real-Word Reading Accuracy test, the Real-Word Reading Speed test, the Non-Word Reading Accuracy test and the Non-Word Reading Speed test (de Jong & Wolters, 2002), were administered. These tests were adapted to the Flemish curriculum and age norms were collected in a large-scale pilot study (Peeters, 2005).

2.2.6.2. Spelling. A standardized spelling achievement test (Dudal, 1997) was used to assess children’s spelling abilities. Children were required to spell single words presented in isolation, single words presented in a sentence context, and short sentences.

2.2.6.3. Pseudohomophone task. To assess passive spelling skills, a pseudohomophone task was administered. In this task 40 familiar words were presented on a screen together with a non-word with the same pronunciation (e.g., “brain” vs. “brane”), and the child was asked to indicate the correctly spelled word.

2.3. Data collection

Data collection was carried out by qualified psychologists and audiologists. All tests were individually administered during several sessions adding up to approximately 10 h of testing per child. Testing took place in a quiet room at the children’s school. Phonological measures, letter knowledge, FM and CM detection, and speech perception were assessed in the last year of kindergarten (mean age = 5 years 6 months). Phonological measures, letter knowledge and FM data were collected in three days during the third and fourth month of the school year (November and December). CM detection and speech perception data were collected in one day during month six and seven of the same school year (February and March). Literacy measures (reading, spelling, pseudohomophone task) were collected in the last month (June) of grade 1 (mean age = 6 years 9 months).

2.4. Statistical analysis

Causal path analysis (using Structural Equation Modeling (SEM) techniques) was used to examine the hypotheses. We acknowledge that there exists a pervasive and widespread misconception that advanced covariance structure analysis techniques, like SEM, would only be applicable for large sample studies. Minimum sample size guidelines typically range from 5 to 10 cases per estimated model parameter and recommend a total sample size of at least 100 subjects (e.g., Bentler & Chou, 1987; Tanaka, 1987). These recommendations are justified for the use of the traditional maximum-likelihood chi-square statistic, but they are much too conservative for some of the more recently introduced test statistics. In this respect, Nevitt and Hancock (2004) used Monte Carlo simulations to demonstrate that the application of the Bartlett k-factor correction (Bartlett, 1950) was able to control both type I and type II error rates in sample sizes as small as 50 subjects. In particular when combined with the Satorra–Bentler scaled chi-square test statistic (Satorra & Bentler, 1994), results turned out to be highly robust and powerful, even in small samples and with non-normal data (see Fouladi, 2000; see also Bentler and Yuan (1999) for similar robust results in small samples). Nevitt and Hancock (2004) therefore concluded that “also practitioners with small to moderate sample sizes can effectively model their data and accurately assess data-model fit using SEM techniques’ (p. 468).

To obtain a normal distribution, results on the letter knowledge task and thresholds for FM and CM were log-transformed. CM and FM thresholds were multiplied by −1 to obtain a positive definite covariance matrix; thus, a higher score on a measure indicated a better ability. For two subjects showing a missing test score, data were estimated using the LISREL multiple imputation option. Analysis of the covariance matrices was conducted with LISREL 8.71 (Jöreskog & Sörbom, 2004) and solutions were generated on the basis of maximum-likelihood estimation. To enhance reliability and to reduce the number of estimated parameters of the model, several measures that were theoretically thought to measure the same construct were aggregated into composite variables.

Data screening of the (composite) variables indicated partial data non-normality, both at the univariate and the multivariate level. Therefore, in all models the asymptotic covariance matrix was used as input and the Satorra–Bentler Scaled chi-square test with Bartlett’s k-factor correction was inspected (SBS-$\chi^2$). To evaluate model goodness of fit, the Comparative Fit Index (CFI), the Root Mean Square Error of Approximation (RMSEA) and the Standardized Root Mean Square Residuals (SRMR) were selected. According to Hu and Bentler (1999), the com-
combined cut-off values close to .95 for CFI, below .08 for RMSEA and below .09 for SRMR indicate good model fit.

3. Results

3.1. Descriptive statistics

Table 1 presents maximum possible scores, means, standard deviations and ranges for the administered measures. This table indicates that the data are well distributed without ceiling or floor effects. With regard to preschool letter knowledge, it should be noted that children knew on average less than three letters. Because even the best performing child was not able to name all 16 high-frequent letters, it might be concluded that all children were essentially pre-readers.

3.2. Preliminary analyses

Variables theoretically thought to measure the same construct were combined for data reduction purposes. First, a principal component factor analysis with varimax rotation confirmed that the measures of phonological ability could be grouped according to the traditional threefold structure: (a) a phonological awareness factor, with high loadings of the three sound identity tasks and the rhyme test, (b) a rapid automatic naming factor, with high loadings on color and object naming and (c) a verbal short-term memory factor, with high loadings on non-word repetition and digit span (see Boets et al., 2006a). Consequently, composite scores were calculated for each phonological factor (i.e., AWARENESS, RAN and VSTM) by averaging the standardized scores of their constituent tests.

Second, two composites of literacy achievement were calculated. A reading composite (READING) was created by averaging the z-scores of the six reading tests. A spelling composite (SPELLING) was formed by averaging the z-scores of the spelling and the pseudohomophone test.

Third, a SPEECH composite was calculated averaging the z-scores of the proportion correctly perceived words for the −4 and −7 dB SNR conditions.

Fourth, for FM and CM detection, the average of the best and second best threshold was used as an indicator of a child’s sensory sensitivity (see Boets et al., 2006a for a justification of this approach).

Finally, a preschool measure for orthographic ability was constructed. In the magnocellular theory, dynamic visual processing is thought to determine literacy development through orthographic ability. Because it is impossible to administer a pure orthographic test in preschool, letter knowledge might be the best approximate measure of orthographic ability. However, letter knowledge reflects both orthographic and phonological skills, because solving a letter knowledge task relies on recognizing the visual features of the written symbol and retrieving the corresponding linguistic information. To construct a more pure orthographic measure, we extracted all the phonological aspects out of the letter knowledge task by statistically

removing all the variance due to differences in phonological awareness, rapid automatic naming and verbal short-term memory (see Boets et al., 2006b). This resulted in the newly created variable ORTHOGRAPHY.

3.3. Correlational analyses

Correlations between composites are shown in Table 2. As expected, both dynamic sensory processing measures (FM and CM) were significantly related. Dynamic visual processing (CM) was related to orthographic ability and dynamic auditory processing (FM) was related to speech perception and phonological awareness. Phonological awareness was significantly related to RAN and VSTM, who themselves were unrelated. Reading ability was significantly related to auditory and visual dynamic processing (FM and CM), orthographic ability, speech perception, phonological awareness, RAN and VSTM. Spelling was significantly related to orthographic ability, speech perception, phonological awareness and VSTM. Reading and spelling were highly correlated. It should be noted that the reported associations were generally larger in the low-risk group compared to the high-risk or total group. This suggests that the total group correlations were not inflated because of aggregating data over extreme groups. Likewise, visual inspection of all scatter plots confirmed that the observed relations were not determined by outlying subjects.

3.4. Path model for reading and spelling achievement

A test of the theoretical model depicted in Fig. 1 resulted in a moderate global fit (SBS-$\chi^2(18) = 25.41$, $p > .10$; CFI = .94; RMSEA = .09; SRMR = .11). All the path coefficients were significant, except the SPEECH $\rightarrow$ RAN path, the SPEECH $\rightarrow$ VSTM path, the RAN $\rightarrow$ READING, the RAN $\rightarrow$ SPELLING path and the correlation between RAN and VSTM. To verify whether addition or deletion of paths would improve the model fit, a model trimming strategy was applied in which we initially allowed all possible relations and systematically omitted the non-significant paths. Application of this strategy resulted in the excellently fitting structural model depicted in Fig. 2 (SBS-$\chi^2(15) = 12.50$, $p > .25$; CFI = 1.00; RMSEA = 0.00; SRMR = .07). According to this model, 49% of the variance in reading and 35% of the variance in spelling could be predicted. In this final model, the five abovementioned insignificant paths were omitted and three supplementary paths were added.

First, besides the significant speech-mediated path (FM $\rightarrow$ SPEECH $\rightarrow$ AWARENESS: $\beta = .33$, $p < .01$ and $\beta = .35$, $p < .001$, respectively), the direct FM $\rightarrow$ AWARENESS path also turned out to be highly significant ($\beta = .36$, $p < .001$). Due to adding this direct path, the SPEECH $\rightarrow$ AWARENESS path became insignificant ($\beta = .17$, $p > .05$), which suggests that dynamic auditory processing influences phonological awareness in a rather direct way and is only marginally mediated by speech perception
Second, the direct SPEECH \rightarrow READING path was retained ($\beta = .21, p < .01$), in addition to the phonologically mediated SPEECH \rightarrow AWARENESS \rightarrow READING path ($\beta = .33, p < .001$ and $\beta = .43, p < .001$, respectively). This suggests that phonological awareness indeed partially mediates the relation between speech perception and reading development. Note that in the final model depicted in Fig. 2 the initially significant SPEECH \rightarrow AWARENESS path is reduced as a consequence of adding the direct FM \rightarrow AWARENESS path and not as a consequence of adding the direct SPEECH \rightarrow READING path.

Third, besides the fully orthography-mediated path the direct CM \rightarrow READ path was also significant ($\beta = .20, p < .05$). As both path coefficients from the indirect path were also retained ($\beta = .29, p < .05$ and $\beta = .21, p < .05$, respectively), this indicates that the relation between dynamic visual processing and literacy development is at least partially mediated by orthographic ability.

To verify the stability of the model, the analysis was repeated on the data partialed out for individual differences in non-verbal intelligence. The fit indices and path coefficients of the resulting model were nearly identical to the ones presented in Fig. 2, with the exception that the SPEECH \rightarrow AWARENESS path became significant again ($\beta = .19, p < .05$).

To verify whether the inferred causal model would apply to each of both groups, the abovementioned analysis was carried out for the high-risk and low-risk group separately.

(see Holmbeck, 1997, for a clear conceptual and statistical definition of mediation).

Table 2

<table>
<thead>
<tr>
<th></th>
<th>RCPM</th>
<th>CM</th>
<th>ORTHOGRAPHY</th>
<th>FM</th>
<th>SPEECH</th>
<th>AWARENESS</th>
<th>RAN</th>
<th>VSTM</th>
<th>READING</th>
<th>SPELLING</th>
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</thead>
<tbody>
<tr>
<td>CM</td>
<td>.25</td>
<td>–</td>
<td>.26**</td>
<td>.27*</td>
<td>.12</td>
<td>–</td>
<td>.04</td>
<td>.05</td>
<td>.07</td>
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<td>–</td>
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Note: Coefficients above the diagonal are partial correlations after removing variance attributable to individual differences in non-verbal intelligence (RCPM, Raven Coloured Progressive Matrices).

* $p < .05$.
** $p < .01$.
*** $p < .001$.
**** $p < .0001$.

Fig. 2. Path analysis predicting first grade reading and spelling achievement. $p < .05$, **$p < .01$ and ***$p < .001$. 
These analyses should, however, be interpreted with caution because the sample sizes were very small, even in view of Bartlett’s $k$-factor correction. For the high-risk group, a test of the final model resulted in a satisfying global fit ($SBS-\chi^2(15) = 15.63$, $p > .25$; CFI = .96; RMSEA = .07; SRMR = .09). Compared to the total group analysis, the main differences at the path level were the marginally significant FM $\rightarrow$ SPEECH path and the insignificant VSTM $\rightarrow$ READING and VSTM $\rightarrow$ SPELLING paths. This suggests that in the high-risk group (a) speech perception and auditory processing act rather independently upon phonological awareness, and (b) verbal short-term memory does not explain any unique variance in reading and spelling ability. For the low-risk group, the inferred final model showed a somewhat less good fit ($SBS-\chi^2(15) = 22.16$, $p > .10$; CFI = .91; RMSEA = .15; SRMR = .098). Compared to the total group, main differences at the path level were the insignificant CM $\rightarrow$ ORTHOGRAPHY and AWARENESS $\rightarrow$ SPELLING path. This implies that for the low-risk group (a) the visual pathway towards reading development seems to be less mediated by orthographic ability, and (b) phonological awareness does not explain any unique variance in spelling ability.

4. Discussion

This study investigated the interrelations between preschool measures of auditory and visual dynamic sensory processing, speech perception, orthographic and phonological ability, and first grade measures of reading and writing achievement. By studying pre-reading children and applying a longitudinal prospective design, we were able to evaluate the directionality of these relations. Although this study is situated within the general magnocellular theory of dyslexia, we do not aim to make any claims regarding the underlying neurobiological deficits that have been hypothesized.

The empirically deduced model (Fig. 2) fits fairly well with the basic assumptions of the general magnocellular theory. Dynamic auditory processing was related to speech perception, which on its turn was related to phonological awareness. Similarly, dynamic visual processing was related to orthographic ability. Phonological awareness and orthographic ability, together with verbal short-term memory, were unique predictors of literacy development. Unexpectedly, the model fit could be significantly improved by allowing a direct influence of dynamic auditory processing upon phonological awareness. This indicates that this determination happened in a direct way and was only marginally mediated by speech perception. For reading, there also was an additional direct influence of speech perception next to the influence mediated by phonological awareness. Similarly, dynamic visual processing also exerted a direct influence upon reading development next to the orthography-mediated influence. For spelling, these two additional direct paths were not retained. A possible explanation for the retention of the additional direct path from dynamic visual processing towards reading and not towards spelling achievement, might be the relatively larger involvement of magnocellular driven processes, like eye movement control and peripheral vision, in reading compared to spelling.

Similar to McBride-Chang (1996), Watson and Miller (1993) and Schulte-Körne et al. (1999), we showed a significant relation between speech perception and phonological processing. However, we only demonstrated a significant influence of speech perception on phonological awareness, whereas McBride-Chang (1996) and Watson and Miller (1993) also observed an influence of speech perception on rapid automatic naming and verbal (short- and long-term) memory. Furthermore, we also found a direct influence of speech perception on reading besides the phonology-mediated influence, which contrasts the findings of Watson and Miller (1993) and Schulte-Körne et al. (1999). With regard to auditory temporal measures, dynamic auditory processing exerted both a direct and an indirect (speech-mediated) influence on phonological awareness. This finding contrasts with the results of Watson and Miller (1993), who demonstrated that auditory temporal processing did not additionally predict phonological processing when the influence of speech perception was already taken into account. However, they did not explore the theoretically more relevant hypothesis whether speech perception might be determined by auditory processing.

In the present study, the visual and auditory pathways of the general magnocellular theory were examined simultaneously. Our preschool data are in line with previous studies on adults and school-aged children. These data demonstrate that dynamic auditory sensitivity seems to be uniquely related to phonological skills, and that dynamic visual sensitivity is exclusively related to orthographic skills (Talcott & Witton, 2002; Talcott et al., 2000a,b). Moreover, our data indicate that these relationships are already prominent in preschool, before children learned to read. By showing that auditory and visual temporal processing are related to different precursors of reading, our results corroborate and extend the longitudinal findings of Hood and Conlon (2004), who demonstrated that preschool measures of auditory and visual temporal order judgement significantly predicted first grade reading achievement.

Preschool phonological processing and early literacy skills were significantly related, which fits the available research evidence from previous prospective studies (e.g., Scarborough, 1998, for a review). Each of the three phonological subskills was associated with reading. For phonological awareness and verbal short-term memory, the magnitude of these relations was in line with other prospective studies; for rapid automatic naming the association with reading was a bit reduced. When all three skills were included simultaneously, together with orthographic ability, in an analysis to predict literacy, only phonological awareness and verbal short-term memory emerged as unique predictors. This was somehow unexpected, because in the prediction of reading achievement, phonological
awareness and verbal short-term memory generally tend to share more common variance, while rapid automatic naming appears to be a more distinct predictor (Bowers & Ishaik, 2003). As noted by Elbro and Scarborough (2003), the relative importance of a predictor of reading skill depends on two factors: (a) the level of reading proficiency one aims to predict and (b) the specific reading skill assessed. First, in the initial stages of reading development, when reading mostly depends on phonological decoding, phonological awareness is of major importance. During later stages, decoding speed gains more importance and rapid automatic naming becomes a more important predictor, particularly in languages with transparent orthographies (van den Bos, Zijlstra, & Spelberg, 2002). As we assessed reading after children received only one school year of formal instruction, their reading ability was not yet automated and still drew mainly upon phonological decoding and, consequently, upon phonological awareness. Second, we mainly evaluated reading skills by means of accuracy measures. Because reading accuracy appears to be more closely related to phonological awareness and reading speed is more associated with rapid automatic naming (de Jong & Wolters, 2002; Savage & Frederickson, 2005), this probably explains the reduced predictive power of rapid automatic naming in our study. Indeed, when only reading speed measures were considered, an increased correlation between rapid automatic naming and reading was observed.

With respect to the causality of the observed relations between basic sensory processing and literacy skills, it has been suggested that better sensorial sensitivity might be a consequence and not a cause of better literacy skills (Talcott & Witton, 2002). Likewise, it has been suggested that the temporal processing deficits found in dyslexia could be a result, rather than a cause, of the reading failure (Ramus, 2004). However, by studying pre-reading children and applying a prospective longitudinal design, we were able to control the autoregressive effects of previous reading ability. We showed (1) that sensory problems generally precede the literacy problem (Boets, De Smedt et al. 2007; Boets, Wouters et al. 2007), and (2) that preschool dynamic sensory processing is significantly related to later literacy achievement. Although we are still unable to discern whether the sensory problems are the cause of the literacy problem or whether they are a non-causally related marker of it, the current study convincingly demonstrated that the observed sensory deficits and relations are not merely a consequence of reading failure or variation in reading ability.

Because all measures of sensory processing, speech perception, and orthographic and phonological ability were collected before children were able to read, it seems evident that any relation with later literacy development should be conceptualized as unidirectional and predictive. By contrast, the nature of the relations within the group of simultaneously administered preschool measures is much less straightforward. Similar to the established observation that phonological awareness and literacy development influence each other in a bidirectional way (e.g., Morais, Bertelson, Carey, & Alegría, 1979; Perfetti, Beck, Bell, & Hughes, 1987; Read, Zhang, Nie, & Ding, 1986), there is growing evidence that auditory processing, speech perception and phonological ability influence each other reciprocally. For example, some intervention studies demonstrated that speech discrimination is causally related to development in phonological skills (Hurford, 1990; Moore, Rosenberg, & Coleman, 2005), whereas others show that progression in phonological awareness seems to stimulate (or at least precede) development in auditory processing and speech perception (Mayo et al., 2003; Warrier, Johnson, Hayes, Nicol, & Kraus, 2004). This indicates that the relation between auditory processing, speech perception and phonological awareness is probably a bidirectional one. Nevertheless, the bidirectional character of these relations does not essentially conflict with the basic assumptions of the general magnocellular theory. It is very well possible that minor initial problems in sensory processing will multiply up to more serious deficits exactly because of the reciprocal nature of these relations.

We acknowledge that the present data appear to be at odds with conclusions from a previous report on the same sample of children. Based on individual subject data, Boets, Wouters et al. (2007) found that only about 40% of literacy-impaired subjects showed auditory and speech perception problems whereas 80% of them had phonological problems. Because there was also a fairly low rate of co-occurrence between these problems, Boets, Wouters et al. (2007) concluded that auditory and speech perception problems are probably not the main origin of the phonological and literacy problems. These data were interpreted as being rather unfavorable of the auditory pathway of the general magnocellular theory. There are several reasons why the current path model might be more supportive of the general magnocellular theory than Boets, Wouters et al. (2007). First, the present model might be unduly influenced by a few extreme cases. We therefore repeated all analyses while excluding subjects that scored exceptionally well or poor. This re-analysis did not alter the model fit or path coefficients. Second, our model may actually not reflect a relationship between perceptual deficit and literacy deficit, but an association between perceptual ability and literacy ability (see Bradley & Bryant, 1985, for a similar account on the strong prediction of reading from preschool phonological awareness). This implies that the model would provide an accurate description of the causal path leading to normal literacy development, but not of the path leading to impaired literacy development. A separate analysis of the high-risk versus low-risk group did not support this idea, as the model showed a better fit in the high-risk group, which comprised more literacy-impaired subjects. Ideally, this analysis should have been carried out on subgroups of normal reading versus impaired reading children, but this was practically impossible due to small sample sizes. Third, Boets, Wouters et al. (2007) might have put
too much emphasis on individual subject analyses. Indeed, at the group level they did observe significant preschool deficits in dynamic auditory and visual processing, speech perception, phonology and orthography in literacy-impaired subjects (see also Boets, 2006). These group data support the general magnocellular theory and the causal path model presented here. However, at the level of the individual subjects, this deficit could not be demonstrated in every single subject. This observation is not too surprising given that research in social sciences generally not adheres in the same absolute manner to fundamental laws as is the case in physical sciences. Moreover, in the theoretical causal chain towards literacy development, sensory processing is a much more distal factor than phonology, which is more closely related to the process of learning to read. This might explain why the proportion of literacy-impaired subjects with sensory deficits was smaller than the proportion of literacy-impaired subjects with deficits in phonology.

Overall, the group level data of Boets (2006) and Boets, Wouters et al. (2007) together with the present causal path study suggest that sensory problems generally precede the literacy problem and are significantly related to it. Although this pattern could not be demonstrated in every single literacy-impaired subject, the global evidence favors the hypothesis of a potential causal influence of sensory processing upon literacy development as postulated by the general magnocellular theory.

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