Available online at www.sciencedirect.com

SCIENCE DIRECT®

Vision Research 46 (2006) 527–535

Vision Research

www.elsevier.com/locate/visres

Coherent motion detection in preschool children at family risk for dyslexia

Bart Boets [a,*], Jan Wouters [b], Astrid van Wieringen [b], Pol Ghesquière [a]

[a] Centre for Disability, Special Needs Education and Child Care, University of Leuven, Belgium
[b] Laboratory for Experimental ORL, University of Leuven, Belgium

Received 10 February 2005; received in revised form 13 May 2005

Abstract

We tested sensitivity to coherent motion (CM) in random dot kinematograms in a group of 5-year-old preschool children genetically at risk for dyslexia, compared to a group of well-matched control children. No significant differences were observed, either in a group analysis or in an individual deviance analysis. Nonetheless, CM-thresholds were significantly related to emerging orthographic skills. In a previous study on the same subjects (Boets, Wouters, van Wieringen, & Ghesquière, in press), we demonstrated that both risk groups already differed on measures of phonological awareness and letter knowledge. Moreover, auditory spectral processing (especially 2 Hz FM detection) was significantly related to phonological ability. In sum, the actual visual and previous auditory data combined, seem to suggest an exclusive relation between CM sensitivity and orthographic skills on the one hand, and FM sensitivity and phonological skills on the other.

Keywords: Dyslexia; Preschool children; Motion Coherence; Auditory frequency modulation; Magnocellular

1. Introduction

Developmental dyslexia is a specific failure to acquire reading and spelling skills despite adequate intelligence and education, affecting around 5–10% of children and adults. The predominant etiological view postulates that dyslexia results from a phonological deficit (Snowling, 2000). However, extensive research during the last decade also demonstrated a specific sensory processing deficit in individuals with dyslexia and it has been suggested that this deficit might be causal to both the observed phonological and literacy problems (Farmer & Klein, 1995; Stein, 2001). To investigate the assumed causality of this sensorial deficit hypothesis we assessed auditory and visual processing in two contrasting groups of 5-year-old preschool children, a genetically high risk and a genetically low risk group. In a previous paper (Boets, Wouters, van Wieringen, & Ghesquière, in press) we reported the absence of a significant group difference for any of three administered auditory measures, in the presence of a significant difference for phonological awareness and letter knowledge. However, spectral auditory tasks (particularly 2 Hz frequency modulation detection) turned out to be highly significantly related to phonological awareness. In this paper, we will focus upon sensory processing in the visual modality, assessed in the same group of preschool children. In particular, we consider the question whether a deficit in coherent motion processing may already be observable in preschool children at risk of dyslexia and we investigate the relationship between motion processing and developing literacy skills.

Within the visual modality, dyslexia research has mainly focused upon sensory processing in the magnocellular visual pathway. Early studies using stimuli that assess the peripheral visual system (e.g., contrast sensitivity and flicker sensitivity paradigms) demonstrated that dyslexics tend to show a deficit in processing stimuli with low spatial

* Corresponding author. Tel.: +32 016 32 61 82; fax: +32 016 32 59 33.
E-mail address: bart.boets@ped.kuleuven.be (B. Boets).

0042-6989/$ - see front matter © 2005 Elsevier Ltd. All rights reserved.
doi:10.1016/j.visres.2005.08.023

and high temporal resolution (for a review, see Lovegrove, 1996; but see Skottun, 2000 for a critical revision). More recently, interesting results have also been obtained with stimuli that imply higher level magnocellular functioning such as coherent motion detection tasks (CM). These tasks, relying predominantly upon processing in area V5/MT of the cortex, have proven to differentiate relatively reliable between groups of dyslexic and normal reading subjects (Cornelissen, Richardson, Mason, Fowler, & Stein, 1995; Everatt, Bradshaw, & Hibbard, 1999; Hansen, Stein, Orde, Winter, & Talcott, 2001; Raymond & Sorensen, 1998; Ridder, Borsting, & Banton, 2001; Talcott, Hansen, Assoku, & Stein, 2000; Talcott et al., 2003; Van Ingelghem, Boets, van Wieringen, Ghesquière, & Wouters, 2004; Wilmer, Richardson, Chen, & Stein, 2004; Witton et al., 1998). Moreover, functional imaging studies have confirmed that activation of area V5/MT in response to coherent motion stimuli was not as robust in dyslexics compared to controls (Eden et al., 1996). Demb, Boynton, and Heeger (1997) have even demonstrated a reliable relation between the magnitude of the hemodynamic BOLD-response in extrastriate area MT and overall reading skills in dyslexic subjects. In psychophysical studies too, sensitivity to motion stimuli has been related to (nonword) reading ability (Talcott et al., 1998; Van Ingelghem et al., 2004; Witton et al., 1998), orthographic ability (Talcott, Hansen, et al., 2000; Talcott, Witton et al., 2000; Talcott et al., 2002; Van Ingelghem et al., 2004) and letter position encoding (Cornelissen et al., 1998). However, evidence of a motion coherence deficit in dyslexia is not yet unequivocal since some studies failed to find differentiating thresholds (Amitay, Ben-Yehudah, Banai, & Ahissar, 2002; Hulslander et al., 2004; Kronbichler, Hutzler, & Wimmer, 2002; Ramus et al., 2003). Moreover, a deficit in motion processing might not be an exclusive characteristic of dyslexia, since it has also been demonstrated in other developmental disorders like for example autism (Milne et al., 2002) and Williams-syndrome (see e.g., Atkinson et al., 1997).

Regarding the specific mechanism by which coherent motion sensitivity may limit normal literacy development, there is still much speculation. Since CM-thresholds are a robust measure of magnocellular processing and since this visual subsystem is mostly involved in encoding spatial information, it is probable that poor magnocellular functioning might result in uncertainty about letter position while reading and writing (Cornelissen et al., 1998). Furthermore, a magnocellular deficit has also been related to binocular instability and poor eye movement control, visual attention and visual search—all factors that might interfere with the development of orthographic skills and subsequent reading and spelling skills (Stein & Talcott, 1999; Stein, 2001; Talcott, Hansen, et al., 2000; Talcott, Witton et al., 2000).

Notwithstanding the considerable empirical evidence that CM-thresholds are able to differentiate reliably between adult and school-aged dyslexic and normal reading subjects, the differentiating and predictive power of this task has never been investigated in preschool children. In this study, we want to address this issue. Furthermore, to investigate the specific relation between sensory processing and different aspects of literacy development, we will also integrate the previously administered phonological measures and the 2 Hz FM detection thresholds in our correlation analyses. This has been done since in a series of former studies CM detection has gradually been linked to FM detection (see e.g., Witton et al., 1998; Talcott, Hansen, et al., 2000; Talcott, Witton et al., 2000; Talcott et al., 2002; Talcott et al., 2003). According to Talcott, Witton, and colleagues both psychophysical tasks could be regarded as 'dynamic' stimuli tasks by relying upon long-duration stimuli that require the perception of a dimension changing in time ('perception of rate'). While CM detection depends on the successful detection and integration of local motion signals over both time and space, FM detection depends on tracking the dynamic changes in the frequency of a tone over time. Interestingly, in some recent studies where FM and CM-detection tasks have been administered to the same subjects (school-aged children), it has been demonstrated that orthographic skills co-vary most strongly with CM sensitivity, whereas phonological skills co-vary most strongly with FM sensitivity (Talcott, Hansen, et al., 2000; Talcott, Witton et al., 2000; Talcott & Witton, 2002). In this study we will explore whether these specific relations might already be present in preschool subjects.

2. Materials and methods

2.1. Participants

Sixty-two 5-year-old children attending the last year of kindergarten[1] were included in the study (36 boys/26 girls). Half of the participants were children of 'dyslexic families', the so-called high-risk group (HR); the other half were control children of 'normal reading families,' the so-called low-risk group (LR). All children were native Dutch speakers without any history of brain damage, long term hearing loss or visual problems. Additionally, at the moment of data collection they did not present any gross deficiencies in visual acuity (Landolt-C single optotypes Snellen acuity >0.85) and/or audiology (audiometric pure-tone average <25 dB HL). The HR children were selected on a basis of having at least one first-degree relative with a diagnosis of dyslexia. The LR children showed no history of speech or language problems and none of their family members suffered any learning or language problems. For every individual HR child we selected the best matching LR control child based on five criteria: (1) educational environment, i.e., same nursery school, (2) gender, (3) age, (4) nonverbal intelligence, and (5) parental educational level. Nonverbal intelligence was assessed by an adapted version of the Raven Coloured Progressive Matrices (RCPM) (Raven, Court,

[1] In the Belgian school system formal instruction starts in Grade 1 at 6 years. This means in kindergarten no reading instruction is offered.

Table 1
Characteristics of participants and coherent motion detection thresholds

Measures	HR		LR		p
	M	SD	M	SD	
Nonverbal IQ	107	14	111	13	.07[a]
Age in months	68	3	68	3	.83[a]
Best CM1 (% coherence)	0.19	0.11	0.17	0.08	.28[b]
Best CM2 (% coherence)	0.22	0.13	0.19	0.09	.14[b]
AV CM1/2 (% coherence)	0.20	0.12	0.18	0.09	.19[b]

Note. BestCM1-2: best and second best CM threshold, AVCM1/2: average of the two best CM thresholds.
[a] Paired *t* test.
[b] Paired wise MMA controlled for nonverbal IQ, age and parental educational level.

& Raven, 1984), a collective non-verbal intelligence test measuring spatial reasoning. Parental educational level was assessed using the ISCED-scale (International Standard Classification of Education by UNESCO, 1997), by converting classifications on the original seven-point scale to a three-point scale. Further details about the participants and the selection procedure are described in Boets et al. (in press).

Table 1 gives descriptive characteristics of both groups. At the time of collecting the visual data the mean age for both the HR and LR group was 5 years and 8 months, not being statistically different ($p = .83$). The nonverbal IQ scores were slightly above population average (107 for HR group and 111 for LR group) and did not differ significantly ($p = 0.07$). Fisher's Exact Test also confirms that both groups did not differ in frequency distribution of the different educational categories ($p = .71$ for maternal and $p = .43$ for paternal educational level).

2.2. Apparatus

2.2.1. Phonological tests

Phonological skills were assessed by a broad test battery comprising eight tests. A principal component factor analysis with varimax rotation confirmed that the battery reflected the three traditional phonological domains: (a) *phonological awareness* (Phon Awareness): high loadings from first-sound and end-sound identity task, rhyme identity task and simple rhyme task, (b) *rapid automatic naming* (RAN): high loadings from both the colours and objects rapid automatic naming tasks and (c) *verbal short-term memory* (Verbal STM): high loadings from the nonword repetition task and the digit span forward task. Details about the composition of the battery can be found in Boets et al. (in press); in this paper, we will only refer to the factor scores.

2.2.2. Productive letter knowledge

This task was intended as a preliminary measure of literacy development. The 16 most frequently used letters in Dutch books were presented on a card and the child had to name each of these letters. Both the sound and the name of a letter were considered correct.

2.2.3. CM-detection test

For the CM-detection test, children were sitting in a low-luminance (mesopic) environment at 40 cm distance from an Elo Intuitive 1725L 17 in. touch screen (75 Hz refresh rate) on which the random dot kinematograms (RDK) were displayed. The display resolution was set to 640×480 pixels. The stimuli were generated online by a portable computer (Dell Latitude C800 and Toshiba Satellite 1400-103) and comprised of two rectangular patches, each containing 1103 randomly moving high luminance white dots on a black background (dot size = 1 pixel or 0.07° diameter, dot density = 2.5 dots/deg^2, velocity = 7.3 deg/s, life time = 5 video frames or 200 ms, maximal duration of stimulus presentation = 6 s, luminance of dots = 125 cd/m^2, luminance of background = 0.39 cd/m^2, Michelson contrast = 99.4%). At a viewing distance of 40 cm each patch of dots subtended $16 \times 27.2°$ visual angle, separated horizontally by 3.8°. The target patch was segregated into three horizontal strips (see Gunn et al., 2002); in the middle strip a variable proportion of dots were moving coherently in horizontal direction, reversing direction every 330 ms—creating as such the impression of 'an emerging road in the snow.' All other dots were moving randomly in a Brownian manner. The two patches were presented simultaneously and the subject had to identify the patch containing the strip with coherently moving dots. Threshold was defined as the smallest proportion of coherently moving dots required for detection of the middle strip with reversing dot motion. Thresholds were estimated using a two-down, one-up adaptive staircase paradigm, which targeted the threshold corresponding to 70.7% correct responses (Levitt, 1971). Percentage coherence in the middle strip of the target patch started at 100% and decreased with a factor of 1.16. After four reversals factor 1.14 was used. A threshold run was terminated after eight reversals and thresholds for an individual run were calculated by the geometric mean of the values of the last four reversals. For every subject four thresholds were determined. Prior to data collection, participants were given a short period of practice, comprising supra-threshold trials, to familiarise them with the stimuli and the task.

To ensure the child's attention and motivation we integrated the psychophysical test in a computer game with animation movies, aimed to transform the abstract meaningless stimuli into a concrete and well-known 'daily life signal.' Before administering the CM-detection experiment children watched an introductory animation movie about a little dog and a little bear getting lost in the snow (see Fig. 2A). The children were asked to help them find their way home again by visually inspecting each stimulus patch and reporting which patch contains the road to get home (inspired by work of Atkinson et al., 2003). Immediately after the child's response, corresponding auditory feedback was presented.

2.2.4. FM-detection test

In this test participants had 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. Modulation depth decreased with a factor 1.2 from 100 towards 11 Hz, from where a fixed step size of 1 Hz was used. The length of both the reference and the target stimulus was 1000 ms including 50 ms cosine-gated onset and offset. Stimuli were generated in MATLAB 5.1 and saved as 16-bit wav-files (sample frequency 44,100 Hz) on the hard disc of the same portable computers as used for the CM-experiment. They were presented using an integrated audio PC-card and routed to an audiometer (Madsen OB622) to control the level of presentation. The stimuli were presented monaurally over a calibrated TDH-39 headphone at 70 dB SPL with an ISI of 350 ms. FM-thresholds were estimated using a three-interval forced-choice oddity paradigm embedded within an interactive computer game with animation movies (see Fig. 2B) (Laneau, Boets, Moonen, van Wieringen, & Wouters, 2005). Similarly to the CM-experiment a two-down, one-up adaptive staircase procedure was used and threshold was calculated as the geometric mean of the values of the last four of eight reversals. After a short period of practice, three thresholds were determined for every subject. For the correlation data we present here, the average of the best and second best threshold was used as an indicator of FM sensitivity. A more detailed description of the stimuli, procedure and results can be found in Boets et al. (in press).

Data collection were carried out by qualified psychologists and audiologists. Testing took place in a quiet room at the children's school. Since the LR child was selected from the HR child's classmates, both children could always be tested in exactly the same circumstances.

2.3. Statistical analysis

Prior to analysis, psychophysical thresholds were $\log_{10}$-transformed to obtain normally distributed data. All results were analysed in a paired wise manner, comparing HR versus LR group at the level of the matched individuals. Although the groups did not show a significant difference on any of the matching criteria, we decided to rule out any possible influence of age, nonverbal intelligence or parental educational level by controlling for these variables in our analysis. As such, we analysed the data using Mixed Model Analysis (MMA) with school as a random variable (1 to 31) and participant group (HR versus LR) as the fixed between-subject variable (Littell, Milliken, Stroup, & Wolfinger, 1996). Age, nonverbal IQ, and educational level of both mother and father were added as fixed (co)variables. Relationships between variables were analysed using Spearman correlation coefficients, partialed out for the influence of nonverbal intelligence.

3. Results

A paired wise Repeated Measures MMA with group as between-subject variable (HR versus LR), threshold run as within-subject variable (run 1–4) and with the same covariates as mentioned above, revealed no significant effect for group ($p = .20$), a significant effect for threshold run ($p < .0001$) and no significant group × run interaction effect ($p = .25$). Post hoc analysis revealed that none of the four CM threshold measures differentiated significantly between HR and LR group. Furthermore, there was only a significant learning effect from the first to the second run; the second, third, and fourth run did not differ significantly from each other.

Although the Repeated Measures MMA revealed a general learning effect from the first to the second run, this tendency did not apply to all subjects. For many of them, the first threshold was better than the second, third or fourth. Moreover, since we are interested in threshold estimation as an indicator of a subject's true sensory capability—i.e., the best level of performance a subject is able to reach, regardless of interfering factors like for example fluctuations in concentration and motivation—average threshold (or the average of the last two or three threshold runs) might not be the most appropriate measure. To cope with the high intrasubject variability which is typical for younger children (see e.g., Wightman & Allen, 1992), a more reasonable estimator is each subject's 'best' performance, or the lowest threshold of the different runs. For this reason we used the average of the best and second best threshold as a true indicator of a child's CM sensitivity. The Spearman rank correlation between this best and second best threshold estimate appeared to be very satisfactory ($r_s = .91$, $p < .0001$), indicating a reliable threshold estimation.

Threshold estimates and test statistics for the best and second best threshold and for the average of the two best thresholds are given in Table 1. Although the observed difference was in the expected direction with the HR-group scoring less well than the LR-group, the coherent motion detection task did not differentiate significantly between the groups. It is worth mentioning that these null-results were not merely the consequence of applying such a strict controlling MMA design, as the results were virtually identical when the analysis was repeated without any covariates added.

Since group comparisons might mask major individual differences, we also carried out an analysis at the subject level. To decide which individual did and did not show abnormal performance, we adopted the two-step criterion as suggested by Ramus et al. (2003). Applying this procedure, the criterion for deviance was placed at 1.65 standard deviations of the 'purified' mean of the LR-group, after first having excluded all deviant LR-subjects (by applying a similar 1.65 *SD* criterion, resulting in the removal of two deviant LR subjects). A distribution analysis on the coherent motion thresholds of the 'restricted' LR-group confirmed the normality of the data. Hence, the 1.65 *SD* deviance criterion corresponds to the fifth percentile and is thus a fairly strict criterion. The individual deviance analysis for the averaged best and second best coherent

Table 2
Spearman (partial) correlations for total group of subjects ($n = 61/62$)

	Age	RCPM	Letter Knowledge	Phon Awareness	RAN	Verbal STM	AV FM 1/2	AV CM 1/2
Letter Knowledge	−0.08	0.26*	—	0.42***	0.09	−0.07	−0.36**	−0.29*
Phonological Awareness	−0.08	0.26*	0.46***	—	−0.02	−0.10	−0.48****	−0.11
RAN	0.25*	−0.21	0.03	−0.08	—	0.02	−0.12	−0.06
Verbal STM	0.07	0.19	−0.02	−0.04	−0.02	—	−0.05	−0.04
AV FM 1/2	0.15	−0.16	−0.40**	−0.49****	−0.08	−0.08	—	0.26*
AV CM 1/2	0.18	−0.30*	−0.33**	−0.18	0.01	−0.10	0.29*	—

Note. Coefficients above the diagonal are partial correlations after removing variance attributable to individual differences in nonverbal intelligence (RCPM).
* $p < .05$.
** $p < .01$.
*** $p < .001$.
**** $p < .0001$.

motion threshold revealed that the proportion of subjects showing abnormal performance was equal in both groups: four subjects in the HR group and four subjects in the LR group scored below the fifth percentile. This corresponded to 13% of each group.

Table 2 shows Spearman rank interrelations between psychophysical thresholds, phonological ability and letter knowledge, and their relation to age and nonverbal IQ. Neither CM, nor FM were related to age, and only CM-detection showed a significant relation to nonverbal intelligence. To exclude the variance attributable to individual differences in intelligence, all further correlations have been partialed out for the influence of nonverbal IQ. Table 3 offers similar Spearman rank correlations for both risk groups separately.

FM-detection was highly significantly related to Phonological Awareness and—to a lesser extent—to Productive Letter Knowledge. There was no correlation with Verbal STM and only in the HR group the correlation with Rapid Automatic Naming was significant. The relation with Phonological Awareness seemed to be the most robust in the LR-group where 37% of the variance in phonological awareness could be predicted from sensitivity to FM. CM-detection on the other hand, turned out to be completely unrelated to any phonological measure, but was significantly related to Letter Knowledge. However, this relation only seemed to hold for the LR-group.

In previous research CM-detection has been found to be specifically related to orthographic skills. Since it is impossible to administer a pure orthographic test at this preschool age, we considered Letter Knowledge as the best approximate measure to obtain an indication about orthographic ability. After all, resolving a letter knowledge task relies on recognizing the visual features of the written symbol on the one hand, and retrieving the corresponding linguistic information on the other. As such, Letter Knowledge might be regarded as a measure that reflects both orthographic and phonological skills. To create 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 STM. Concretely, we calculated the Spearman correlation between CM and Letter Knowledge and added nonverbal IQ, Phonological Awareness, Rapid Automatic Naming, and Verbal STM as partial variables. In doing so, we still observed a significant relation between CM and the orthographic aspects of Letter Knowledge, both in the total group ($r_s = -.27$, $p = .04$) and in the LR-group ($r_s = -.41$, $p = .03$). For the HR-group this relation was considerable but not significant ($r_s = -.31$, $p = .11$). This means, that again the relation turned out to be the most substantial in the LR-group where 17% of the variance in orthographic skills could be predicted from sensitivity to

Table 3
Spearman partial correlations for LR and HR group separately (after removing variance attributable to individual differences in nonverbal intelligence)

	Letter Knowledge	Phonological Awareness	RAN	Verbal STM	AV FM 1/2	AV CM 1/2
Letter Knowledge	—	0.17	0.17	0.01	−0.31*	−0.41**
Phonological Awareness	0.46**	—	−0.11	−0.08	−0.61****	−0.29
RAN	−0.14	−0.04	—	−0.29	0.13	0.11
Verbal STM	−0.18	−0.14	0.30	—	−0.16	0.06
AV FM 1/2	−0.38**	−0.35*	−0.33*	0.07	—	0.44**
AV CM 1/2	−0.19	0.09	−0.25	−0.16	0.08	—

Note. Coefficients above the diagonal concern the LR group ($n = 31$), coefficients under the diagonal concern the HR group ($n = 30$).
* $p < .10$.
** $p < .05$.
**** $p < .001$.

CM-detection. Interestingly, in contrast, the correlation between FM and the orthographic aspect of Letter Knowledge was not significant (in neither of the two groups). Considering the whole of these observations, this seems to imply an exclusive relation between FM and phonological awareness on the one hand, and CM and orthographic skills on the other (see Figs. 1A and B).

Although FM and CM appeared to be related to different and dissociated aspects of literacy development, they also shared some common variance. Indeed, both in the total group and in the LR-group FM and CM were significantly related to each other. Again, this relation was not present in the HR-group. This might imply that both psychophysical tasks (at least in the LR-group) rely upon some common neurological mechanism involved in 'dynamic processing.' Importantly, this hypothesised common mechanism is not involved in psychophysical processing in general, since CM proved to be completely unrelated to two other auditory measures that were also administered to the same subjects (i.e., gap detection in broadband noise and tone-in-noise detection; for details see Boets et al. (in press).

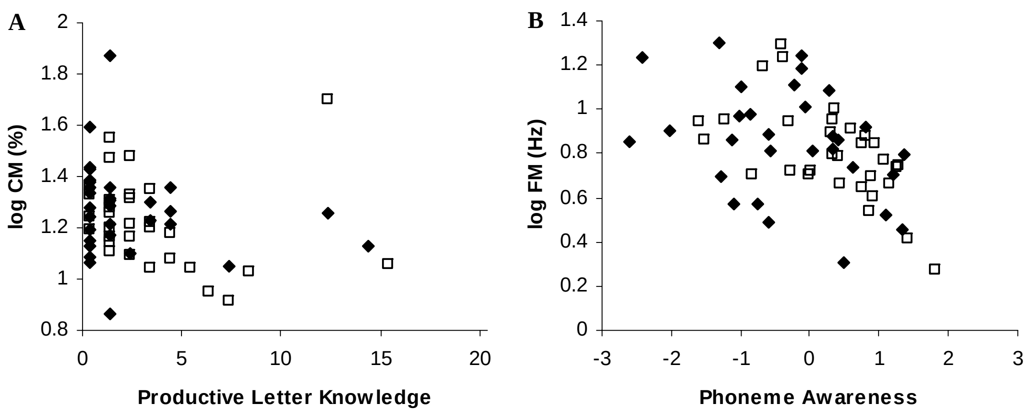

Fig. 1. (A) Thresholds for detecting coherent motion plotted against a Productive Letter Knowledge measure for 31 HR and 31 LR subjects. (B) Thresholds for detecting 2 Hz FM of a 1000 Hz tone plotted against a combined measure of Phonological Awareness for 30 HR and 31 LR subjects. HR subjects: filled diamonds; LR subjects: empty squares.

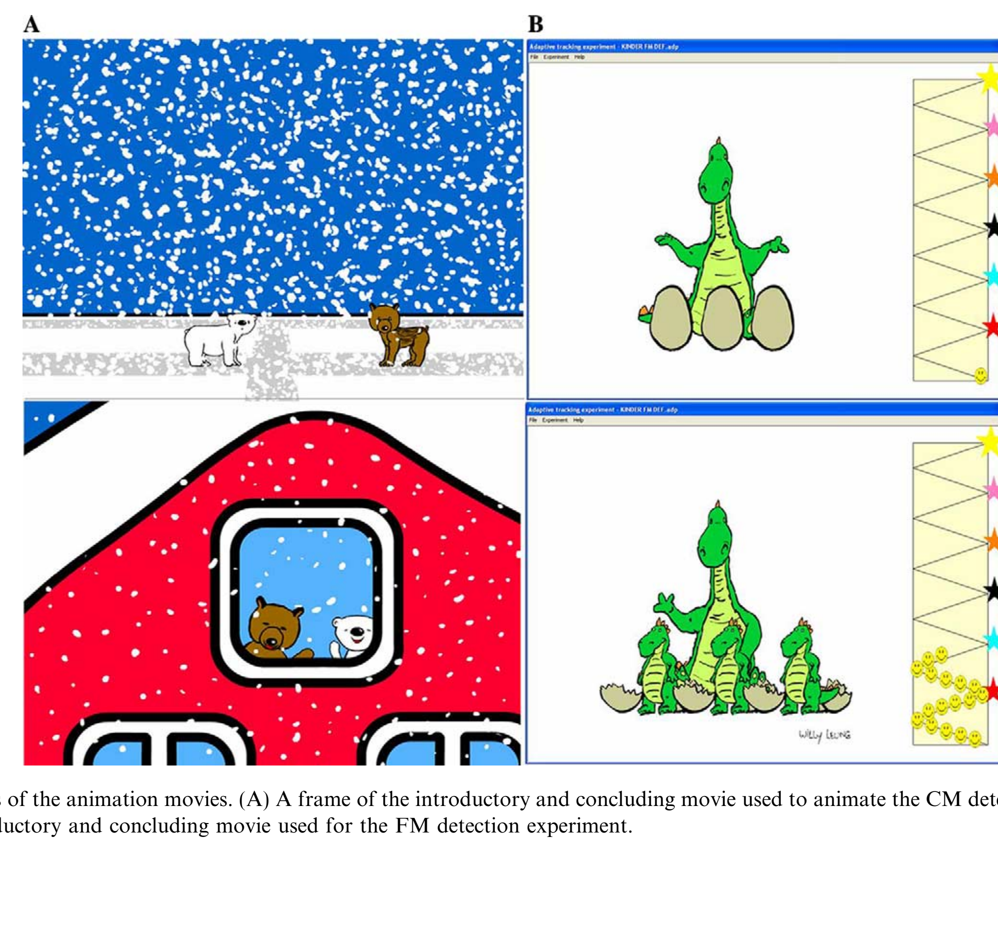

Fig. 2. Screenshots of the animation movies. (A) A frame of the introductory and concluding movie used to animate the CM detection experiment, (B) a frame of the introductory and concluding movie used for the FM detection experiment.

4. Discussion

In this study, we tested sensory processing and phonological and orthographic abilities in 5-year-old preschool subjects who never received any formal reading instruction. As reported previously, a significant deficit in phonological awareness and letter knowledge could be demonstrated in the dyslexia-prone HR group. Consequently, since both letter knowledge and phonological awareness have consistently been proven to be the best preschool predictors of literacy development (see e.g., Scarborough, 1998), it is likely that the genetically high risk group will contain a disproportionally high number of future cases of dyslexia.

For CM detection we did not observe any significant differences between the high and low risk groups, either at a group level, or in the individual deviance analysis. Although these results are consistent with a minority of studies that also failed to find any group differences (Amitay et al., 2002; Hulslander et al., 2004; Kronbichler et al., 2002; Ramus et al., 2003), they clearly conflict with the mass of evidence provided by most other studies. The same applied to the FM detection data that did not reveal a group difference either. A straightforward explanation for this lack of a group difference might be the fact that we did not study a well-defined clinical group but only an at risk group that still might show substantial overlap with the control group. Moreover, Bishop et al. (1999) demonstrated in a twin study on SLI children that in contrast to the highly heritable phonological skills, auditory skills depend less on genetic and more on environmental influences. As such, our finding of a phonological deficit in combination with relatively intact sensorial skills in this genetic high risk group corresponds well with the results of Bishop and colleagues.

Considering the relations between sensory processing and the orthographic and phonological sub skills of literacy development, our preschool data convincingly confirm previous results from adults and school-aged children (Talcott, Hansen, et al., 2000; Talcott, Witton et al., 2000; Talcott & Witton, 2002). Even while taking into account the influence of general cognitive ability, sensitivity to CM seems to be uniquely related to orthographic skills, whereas sensitivity to FM seems to be specifically related to phonological skills. This relation appears to be the most robust in the LR group where 17% of the variance in orthographic skills could be predicted from differences in sensitivity to CM and 37% of the variance in phonological awareness could be predicted from sensitivity to FM.

The finding of these more substantial correlations in the LR/control group compared to the HR/dyslexic group is in line with most other studies (Rosen, 2003). Ahissar, Protopapas, Reid, & Merzenich (2000) have hypothesised that the suppression of these correlations in adult dyslexics might be due to variably compensated literacy skills, in contrast to the lagging sensory skills. However, our data do not provide much support for this interpretation, since we observed a similar pattern in preschool children who have not even been diagnosed or detected as being dyslexic. Actually, the children studied had not yet received any formal reading instruction; indeed, they have had no opportunity to compensate or be treated for their undetected impairments.

With respect to the causality of the observed relations between literacy skills and basic sensory measures, it has been suggested that better sensorial sensitivity might be a consequence and not a cause of better literacy skills (Talcott & Witton, 2002). Indeed, based on adult and school-aged data, the possibility cannot be ruled out that reading experience (or print exposure) improves CM and FM detection performance rather than vice versa. In fact, it would not be too far-fetched to expect visual and auditory skills of good readers to be more finely tuned than those of dyslexics by virtue of their more highly trained orthographic and phonological systems. However, this study on preschool subjects demonstrated that there already exists a reliable preceding relation between sensory and preliminary literacy skills, even before having received any instruction or before having been exposed extensively to a lot of print. Therefore, it seems unlikely to consider the sensorial deficits in dyslexics as a consequence of lack of reading experience. Instead, the results of our study seem to be consistent with the general hypothesis that basic sensory processing skills do influence (albeit in a facilitating or in an inhibiting way) the development of phonological, orthographic and reading abilities.

To conclude, phonological awareness and letter knowledge turn out to be the best indicators to differentiate between preschool children with low versus high genetic risk of developing dyslexia. In contrast, neither visual coherent motion detection nor auditory 2 Hz frequency modulation detection is able to differentiate significantly between both groups. Nevertheless, there is a significant relation between these dynamic sensory measures and developing literacy skills, even while taking into account the influence of differences in intelligence: sensitivity to CM is uniquely related to orthographic skills and not to phonological ability, whereas sensitivity to FM is specifically predictive for emerging phonological skills and not for orthographic skills. In sum, these results suggest that basic visual and auditory sensitivity is likely to play an important role in the development of fine-grained orthographic and phonological representations necessary for successful reading.

Acknowledgments

This research was financed by the Fund for Scientific Research—Flanders (Belgium), Grant G.0216.02. We thank the children and school staff who were involved in this study and we especially show gratitude to Erik Vandenbussche who was one of the inspirators of this project but unfortunately deceased in December 2002. Furthermore, we thank Peter Stiers for stimulating discussion, Kathelijne Jordens for assistance with data collection, Willy Leung for creating the animation movies, Johan Laneau and Aleksander Nowinski for setting up the software for the auditory and the visual test platform, and two anonymous reviewers for helpful comments on previous drafts of this paper.

References

Ahissar, M., Protopapas, A., Reid, M., & Merzenich, M. (2000). Auditory processing parallels reading abilities in adults. *Proceedings of the National Academy of Science of the United States of America, 97*(12), 6832–6837.

Amitay, S., Ben-Yehudah, G., Banai, K., & Ahissar, M. (2002). Disabled readers suffer from visual and auditory impairments but not from a specific magnocellular deficit. *Brain, 125*(10), 2272–2284.

Atkinson, J., King, J., Braddick, O., Nokes, L., Anker, S., & Braddick, F. (1997). A specific deficit of dorsal stream function in Williams' syndrome. *Neuroreport, 8*(8), 1919–1922.

Atkinson, J., Braddick, O., Anker, S., Curran, W., Andrew, R., Wattam-Bell, J., et al. (2003). Neurobiological models of visuospatial cognition in children with Williams syndrome: Measures of dorsal-stream and frontal function. *Developmental Neuropsychology, 23*, 139–172.

Bishop, D. V., Bishop, S. J., Bright, P., James, C., Delaney, T., & Tallal, P. (1999). Different origin of auditory and phonological processing problems in children with language impairment: Evidence from a twin study. *Journal of Speech Language and Hearing Research, 42*(1), 155–168.

Boets, B., Wouters, J., van Wieringen, A., & Ghesquière, P. (in press). Auditory temporal information processing in preschool children at family risk for dyslexia: Relations with phonological abilities and developing literacy skills. *Brain and Language*.

Cornelissen, P., Richardson, A., Mason, A., Fowler, S., & Stein, J. (1995). Contrast sensitivity and coherent motion detection measures at photopic luminance levels in dyslexics and controls. *Vision Research, 35*, 1483–1494.

Cornelissen, P. L., Hansen, P. C., Gilchrist, I., Cormack, F., Essex, J., & Frankish, C. (1998). Coherent motion detection and letter position encoding. *Vision Research, 38*, 2181–2191.

Demb, J., Boynton, G., & Heeger, G. (1997). Brain activity in visual cortex predicts individual differences in reading performance. *Proceedings of the National Academy of Sciences of the United States of America, 94*, 13363–13366.

Eden, G., Van Meter, J., Rumsey, J., Maisog, J., Woods, R., & Zeffiro, T. (1996). Abnormal processing of visual motion in dyslexia revealed by functional brain imaging. *Nature, 382*, 66–69.

Everatt, J., Bradshaw, M., & Hibbard, P. (1999). Visual processing and dyslexia. *Perception, 28*, 243–254.

Farmer, M. E., & Klein, R. M. (1995). The evidence for a temporal processing deficit linked to dyslexia: A review. *Psychonomic Bulletin and Review, 2*(4), 460–493.

Gunn, A., Cory, E., Atkinson, J., Braddick, O., Wattam-Bel, J., Guzzetta, A., & Cioni, G. (2002). Dorsal and ventral stream sensitivity in normal development and hemiplegia. *Neuroreport, 13*(6), 843–847.

Hansen, P. C, Stein, J. F, Orde, S. R, Winter, J. L, & Talcott, J. B. (2001). Are dyslexics' visual deficits limited to measures of dorsal stream function. *Neuroreport, 12*(7), 1527–1530.

Hulslander, J., Talcott, J., Witton, C., DeFries, J., Pennington, B., Wadsworth, S., et al. (2004). Sensory processing, reading, IQ and attention. *Journal of Experimental Child Psychology, 88*, 274–295.

Kronbichler, M., Hutzler, F., & Wimmer, H. (2002). Dyslexia: Verbal impairments in the absence of magnocellular impairments. *Neuroreport, 13*(5), 617–620.

Laneau, J., Boets, B., Moonen, M., van Wieringen, A., & Wouters, J. (2005). A flexible auditory research platform using acoustic or electric stimuli for adults and young children. *Journal of Neuroscience Methods, 142*(1), 131–136.

Levitt, H. (1971). Transformed up-down methods in psychoacoustics. *Journal of the Acoustical Society of America, 49*, 467–477.

Littell, R. C., Milliken, G. A., Stroup, W. W., & Wolfinger, R. D. (1996). *SAS system for mixed models*. Cary, NC: Sas Institute.

Lovegrove, B. (1996). Dyslexia and a transient/magnocellular pathway deficit: The current situation and future directions. *Australian Journal of Psychology, 48*(3), 167–171.

Milne, E., Swettenham, J., Hansen, P., Campbell, R., Jeffries, H., & Plaisted, K. (2002). High motion coherence thresholds in children with autism. *Journal of Child Psychology and Psychiatry, 43*(2), 255–263.

Ramus, F., Rosen, S., Dakin, S. C., Day, B. L., Castellote, J. M., White, S., & Frith, U. (2003). Theories of developmental dyslexia: insights from a multiple case study of dyslexic adults. *Brain, 126*(4), 841–865.

Raven, J. C., Court, J. H., & Raven, J. (1984). *Manual for Raven's Progressive Matrices and Vocabulary Scales*. London: Lewis.

Raymond, J., & Sorensen, R. (1998). Visual motion perception in children with dyslexia: Normal detection but abnormal integration. *Visual Cognition, 5*(3), 389–404.

Ridder, W. H., Borsting, E., & Banton, T. (2001). All developmental dyslexic subtypes display an elevated motion coherence threshold. *Optometry and Vision Science, 78*, 510–517.

Rosen, S. (2003). Auditory processing in dyslexia and specific language impairment: Is there a deficit? What is its nature? Does it explain anything?. *Journal of Phonetics 31*, 509–527.

Scarborough, H. S. (1998). Early identification of children at risk for reading disabilities: Phonological awareness and some other promising predictors. In P. J. Accardo, A. J. Capute, & B. K. Shapiro (Eds.), *Specific reading disability: A view of the spectrum* (pp. 75–119). Timonium, MD: York Press.

Skottun, B. C. (2000). The magnocellular deficit theory of dyslexia: The evidence from contrast sensitivity. *Vision Research, 40*, 111–127.

Snowling, M. J. (2000). *Dyslexia* (2nd ed.). Malden, MA: Blackwell Publishers.

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

Stein, J. (2001). The magnocellular theory of developmental dyslexia. *Dyslexia, 7*, 12–36.

Talcott, J., Hansen, P., Willis-Owen, C., McKinnell, I., Richardson, A., & Stein, J. (1998). Visual magnocellular impairment in adult developmental dyslexics. *Neuro-Ophtalmology, 20*, 187–201.

Talcott, J. B, Hansen, P. C, Assoku, E. L, & Stein, J. F. (2000). Visual motion sensitivity in dyslexia: Evidence for temporal and energy integration deficits. *Neuropsychologia, 38*(7), 935–943.

Talcott, J. B, Witton, C., McLean, M. F, Hansen, P. C, Rees, A., Green, G. G, et al. (2000). Dynamic sensory sensitivity and children's word decoding skills. *Proceedings of the National Academy of Sciences of the United States of America, 97*(6), 2952–2957.

Talcott, J. B, Witton, C., Hebb, G. S, Stoodley, C. J, Westwood, E. A, France, S. J, et al. (2002). On the relationship between dynamic visual and auditory processing and literacy skills; results from a large primary-school study. *Dyslexia, 8*(4), 204–225.

Talcott, J. B., Gram, A., Van Ingelghem, M., Witton, C., Stein, J. F., & Toennessen, F. E. (2003). Impaired sensitivity to dynamic stimuli in poor readers of a regular orthography. *Brain and Language, 87*, 259–266.

Talcott, J. B., & Witton, C. (2002). A sensory linguistic approach to the development of normal and impaired reading skills. Basic functions of language and language disorders. In E. Witruk, A. Friederici, & T. Lachmann (Eds.), *Neuropsychology and cognition series*. Dordrecht, Netherlands: Kluwer Academic Publishers.

Van Ingelghem, M., Boets, B., van Wieringen, A., Ghesquière, & P., Wouters, J. (2004). Auditory and visual temporal processing in dyslexic and normal reading children matched for sex, age and intellectual ability. Paper presented at 6th BDA International Conference, 27–30, University of Warwick, UK.

Wightman, F., & Allen, P. (1992). Individual differences in auditory capability among preschool children. In L. A. Werner & E. W. Rubel (Eds.), *Developmental Psychoacoustics* (pp. 113–134). Washington, DC: American Psychological Association.

Wilmer, J. B., Richardson, A. J., Chen, Y., & Stein, J. F. (2004). Two visual motion processing deficits in developmental dyslexia associated with different reading skills deficits. *Journal of Cognitive Neuroscience, 16*(4), 528–540.

Witton, C., Talcott, J. B., Hansen, P. C., Richardson, A. J., Griffiths, T. D., Rees, A., et al. (1998). Sensitivity to dynamic auditory and visual stimuli predicts nonword reading ability in both dyslexic and normal readers. *Current Biology, 8*(14), 791–797.