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Differential vulnerability of global motion, global form, and biological motion processing in full-term and preterm children

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ABSTRACT

Young children born very prematurely show elevated thresholds for global motion and global form [Atkinson, J. & Braddick, O. (2007). Visual and visuocognitive development in children born very prematurely. *Progress in Brain Research*, *164*, 123–149; MacKay, T. L., Jakobson, L. S., Ellemberg, D., Lewis, T. L., Maurer, D., & Casiro, O. (2005). Deficits in the processing of local and global motion in very low birthweight children. *Neuropsychologia*, *43*, 1738–1748]. In adolescence, those with white matter pathology show reduced sensitivity to biological motion [Pavlova, M., Sokolov, A., Staudt, M., Marconato, F., Birbaumer, N., & Krageloh-Mann, I. (2005). Recruitment of periventricular parietal regions in processing cluttered point-light biological motion. *Cerebral Cortex*, *15*, 594–601; Pavlova, M., Staudt, M., Sokolov, A., Birbaumer, N., & Krageloh-Mann, I. (2003). Perception and production of biological movement in patients with early periventricular brain lesions. *Brain*, *126*, 692–701]. Here, we measured sensitivity to global form, global motion, and biological motion in a sample of 23, five- to nine-year-old children born at <32 weeks gestation, and in 20 full-term controls matched to the clinical sample in age, socioeconomic status, and estimated Verbal IQ. As a group, premature children showed reduced sensitivity, relative to controls, on all three tasks ($F > 4.1$, $p < 0.05$). By computing a deficit score for each task (the ratio between a premature child's threshold and the mean threshold for three age-matched controls) we were able to compare performance across tasks directly. Mean deficit scores were significantly greater than 1 (indicating some level of impairment) for biological motion and global motion ($ps < 0.03$). In contrast, the mean deficit score for global form was not significantly different from 1 (indicating no impairment, relative to age-matched control children). Rates of impairment (deficit score ≥ 2) were four times higher for global motion than for global form ($p < 0.04$); rates of impairment on the biological motion task fell at an intermediate level. In agreement with previous studies, we find impairments in the processing of global motion (Atkinson & Braddick; MacKay et al.) and of biological motion (Pavlova et al.), which are larger than the impairments in the processing of global form (Atkinson & Braddick). In addition, we show that the impairments are not correlated with each other. The differential vulnerability that we observed across tasks could not be accounted for by stereoacuity deficits, amblyopia, or attentional problems. We suspect, instead, that it reflects the fact that these forms of visual processing develop at different rates, and may be differentially vulnerable to early brain injury or atypical neurodevelopment [c.f., Atkinson, J. & Braddick, O. (2007). Visual and visuocognitive development in children born very prematurely. *Progress in Brain Research*, *164*, 123–149; Braddick, O., Atkinson, J., & Wattam-Bell, J. (2003). Normal and anomalous development of visual motion processing: Motion coherence and 'dorsal-stream vulnerability'. *Neuropsychologia*, *41*, 1769–1784].

Over the last several decades, advances in medical care have increased the survival rates of children born very prematurely (gestational age < 32 completed weeks). This has contributed to a steady increase in the prevalence of biologically at-risk infants and children in the population. Numerous studies have documented a variety of impairments that affect many children who were born very prematurely. In particular, these children have been shown to exhibit poorer performance relative to full-term control children on measures of expressive and receptive language, academic performance (reading, spelling and mathematics), attention, memory, and visual processing (e.g., Downie, Jakobson, Frisk, & Ushycky, 2003; Hack et al., 1992; Herrgärd, Luoma, Tuppurainen, Karjalainen, & Martikainen, 1993; Rickards et al., 1993). The visual impairments that have been documented include deficits in visual acuity (Cooke, Foulder-Hughes, Newsham, & Clarke, 2004; Hellgren et al.,

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2007), visuospatial working memory (Caravale, Tozzi, Albino, & Vicari, 2005; Luciana, Lindeke, Georgieff, Mills, & Nelson, 1999), depth perception (e.g., Jakobson, Frisk, & Downie, 2006; O'Connor et al., 2002), and visual attention (Foreman, Fielder, Minshell, Hurrion, & Sergienko, 1997; Jakobson et al., 2006). Difficulties with several aspects of visual motion perception have also been described, including reduced sensitivity to first- and second-order local motion (MacKay et al., 2005), global motion (MacKay et al., 2005), and 2D structure-from-motion (Downie et al., 2003; Jakobson et al., 2006). Increased risk for problems with oculomotor function (e.g., Butcher, Kalverboer, Geuze, & Stremmelaar, 2002; Glass et al., 2008) and visuomotor control (e.g., (Jakobson, Frisk, Knight, Downie, & Whyte, 2001; Luoma, Herrgard, & Martikainen, 1998) have also been documented in this population.

To characterize the visual problems affecting premature children, it is important to know something about the structural and functional organization of the cortical visual system. The cortical visual system is subdivided into two neuroanatomically separate pathways—the ventral and the dorsal stream. According to Milner and Goodale (1993, 1995, 2008), the ventral ("what") stream, connecting primary visual cortex to inferotemporal cortex, supports object recognition and both conscious and 'unconscious' (preconscious) visual perception. In contrast, the dorsal ("how") stream, connecting primary visual cortex to the posterior parietal cortex, plays a key role in visuomotor control. Jakobson and colleagues (Downie et al., 2003; Jakobson et al., 2006; Jakobson et al., 2001) have pointed out that many of the visual deficits (e.g., problems with motion perception, visuospatial attention, depth perception, visuomotor control, and development of graphomotor skills) that are prevalent in preterm children are suggestive of damage or dysfunction in the dorsal stream, specifically.

Further evidence that the development of dorsal stream functions may be more severely compromised than the development of ventral stream functions in preterm children comes from the work of Atkinson and colleagues (Atkinson & Braddick, 2007; Birtles, Braddick, Wattam-Bell, Wilkinson, & Atkinson, 2007). Consistent with previous research (MacKay et al., 2005), Atkinson and Braddick have shown that children born prematurely at very low birthweights exhibit marked deficits in their ability to detect coherent global motion—a skill thought to depend on the functional integrity of the MT complex (Newsome & Pare, 1988; Schenk & Zihl, 1997a), a key area in the dorsal stream (Schenk, Ellison, Rice, & Milner, 2005; Schenk, Mai, Ditterich, & Zihl, 2000). These authors also administered a test of global form perception, performance on which is thought to involve a key ventral stream area, V4 (Wilson & Wilkinson, 1998; Wilson, Wilkinson, & Asaad, 1997). Deficits were also observed on this task in the preterm sample; however, they were smaller in magnitude than those seen in the test of global motion perception.

Why the dorsal stream should be particularly vulnerable in this population is not completely understood. One possibility is that the unusually early visual stimulation that very premature infants are exposed to may, in itself, have a differential effect on the functional development of the dorsal and ventral streams. Support for this idea comes from research involving another group of children whose early visual experience is also atypical, namely those born with cataracts occluding both eyes (Ellemberg, Lewis, Maurer, Brar, & Brent, 2002; Lewis et al., 2002). While both global form and motion processing are compromised in this population, the deficits in global motion perception (which are indicative of dorsal stream dysfunction) are more striking (Ellemberg et al., 2002; Lewis et al., 2002). Specifically, these authors reported that coherence thresholds were 4.9 times higher in the clinical sample than in control children for global motion (Ellemberg et al., 2002), but only 1.6 times higher for global form (Lewis et al., 2002). These results suggest that atypical post-natal visual experience *alone* may play an important role in dorsal stream vulnerability. This may be related to the fact that motion-processing systems in the dorsal stream are undergoing more rapid development during the perinatal period (Atkinson & Braddick, 1992; Braddick, Birtles, Wattam-Bell, & Atkinson, 2005; Braddick, Wattam-Bell, & Atkinson, 1986; Burkhalter, Bernardo, & Charles, 1993; Wattam-Bell, 1991).

Damage to the developing brain may be another factor contributing to dorsal stream vulnerability in preterm children, given that this group is at high risk for various kinds of neurological insults. Very low birthweight (VLBW: <1500 g) children are at particularly high risk. A substantial number of these children experience periventricular brain injury (PVBI) as a result of intraventricular hemorrhage and/or periventricular leukomalacia (Volpe, 1995). An even larger number (20–50%; see Counsell et al., 2003; Horsch et al., 2007; Inder, Wells, Mogridge, Spencer, & Volpe, 2003; Volpe, 2003) experience more subtle but nonetheless significant damage to the developing white matter that is difficult to detect using conventional imaging (i.e., neonatal cranial ultrasound or structural magnetic resonance imaging). Associated abnormalities in overlying cortical regions have also been described (e.g., Ajayi-Obe, Saeed, Cowan, Rutherford, & Edwards, 2000; Martinussen et al., 2005). Interestingly, posterior regions near the parieto-occipital junction show the strongest predilection to both PVBI and diffuse white matter injury (Back, 2006; Back et al., 2001; Back, Riddle, & McClure, 2007; Back & Rivkees, 2004; Goto, Ota, Iai, Sugita, & Tanabe, 1994; Peterson et al., 2003)—a finding that may explain why dorsal stream functions are particularly susceptible to damage in VLBW children (c.f., Jakobson et al., 2006).

1. The Present study

The purpose of the current study was to explore the dorsal stream vulnerability hypothesis by examining global form and motion processing in young children with a history of very preterm birth. We also wanted to compare performance directly on each of these tasks to that seen on a task assessing sensitivity to global structure-from-motion cues present in biological motion displays (c.f., Johansson, 1973). Our interest in including a test of biological motion perception was motivated by two key observations. First, the processing of biological motion involves the integration of form and motion cues (Beintema & Lappe, 2002; Giese & Poggio, 2003). While wide-spread regions have been implicated in the processing of biological motion [including the MT complex, kinetic-occipital area, inferior and superior parietal lobules, lingual and fusiform gyri, intraparietal sulcus, cerebellum, premotor cortex, and amygdala (Bonda, Petrides, Ostry, & Evans, 1996; Decety & Grèzes, 1999; Grèzes et al., 2001; Grossman & Blake, 2001; Grossman et al., 2000; Puce & Perrett, 2003; Saygin, Wilson, Hagler, Bates, & Sereno, 2004; Servos, Osu, Santi, & Kawato, 2002; Vaina, Solomon, Chowdhury, Sinha, & Belliveau, 2001)], this integration is thought to occur primarily in the superior temporal sulcus (STS; Grèzes et al., 2001; Vaina et al., 2001)—an area that receives input from both the dorsal and ventral streams (Oram & Perrett, 1994; Schenk et al., 2000).

A second reason for including a test of biological motion perception in the present investigation was that, in other research, adolescents with PVBI affecting parieto-occipital regions have been shown to exhibit reduced sensitivity to biological motion (Pavlova, Staudt, Sokolov, Birbaumer, & Krageloh-Mann, 2003; Pavlova et al., 2005). What was not clear from these studies, however, was how their difficulties would compare in magnitude to those seen in either global form or global motion perception. By examining all three skills in the same group of preterm children, we were able to examine relationships between children's scores on each of these three tasks. Past research has demonstrated that bilateral lesions involving the MT complex (McLeod, Dittrich, Driver, Perret,

& Zihl, 1996; Vaina, LeMay, Bienfang, Choi, & Nakayama, 1990) or the posterior temporal lobes (Vaina et al., 1990), while severely compromising motion and form processing, respectively, may not interfere with the perception of biological motion. Similarly, lesions to the STS can impair biological motion perception without affecting colour and form perception or object recognition skills, and without compromising some lower level aspects of motion perception (Schenk & Zihl, 1997b; Vaina & Gross, 2004). Observations such as these support the view (Peelen, Wiggett, & Downing, 2006; Poom & Olsson, 2002; Servos et al., 2002) that global perceptual mechanisms involved in the analysis of motion, form, and biological motion can be dissociated. Our goal was to ascertain the relative vulnerability of these three processing systems in preterm children. To do this, we measured coherence thresholds for global motion and global form, and sensitivity to biological motion. Below, we provide brief descriptions of the particular tasks that were used and the dependent variables that were measured; we also present some findings from past research examining the key neural regions recruited during each of these tasks.

1.1. Global motion coherence

Global motion processing requires the perceptual grouping of local motion signals. In the present investigation, we assessed children's ability to process global motion by measuring their sensitivity to coherent global motion in random dot kinematograms. In these displays, a set of coherently moving dots is presented within an array of randomly moving noise dots. An individual's motion coherence threshold is calculated by finding the lowest proportion of dots that must move coherently for the participant to correctly identify the direction of coherent motion (Newsome & Pare, 1988). A high motion coherence threshold is indicative of poor functioning on this task.

Discriminating direction in a global motion coherence task likely involves the MT complex as well as area V3A (Braddick et al., 2001; Braddick, O'Brien, Wattam-Bell, Atkinson, & Turner, 2000; Newsome & Pare, 1988). Not only are these areas activated during viewing of random dot kinematograms, but the degree of motion coherence in the array is also positively associated with the strength of activation in the MT complex (Rees, Friston, & Koch, 2000). This region is considered by Rizzolatti and colleagues to lie in a ventral subdivision of the dorsal stream, which they implicate in the organization of motor activities and in certain aspects of space perception and action understanding (Fogassi et al., 2005; Rizzolatti & Matelli, 2003).

1.2. Global form coherence

Global form is processed by integrating local elements into the percept of a coherent shape or form. Area V4, a major intermediate processing area in the ventral stream (Heywood, Gadotti, & Cowey, 1992; Merigan, 1996; Ungerleider & Mishkin, 1982; VanEssen, Anderson, & Felleman, 1992; Young, 1992), plays a primary role in the perception of global form (Wilson & Wilkinson, 1998; Wilson et al., 1997). In the present investigation, we evaluated sensitivity to intermediate form signals through the use of Glass (or Moiré) patterns (Glass, 1969; Glass & Switkes, 1976). Glass patterns consist of a combination of two arrays of dots that are usually presented in a circular window. Because the second array is a geometrically transformed version of the first, typical viewers perceive a global form or pattern in such displays; this is accomplished by a global linking of contiguous local elements (Dakin & Bex, 2002; Dakin & Bex, 2003; Glass & Switkes, 1976; Kelly, Bischof, Wong-Wylie, & Spetch, 2001; McGraw, Badcock, & Khuu, 2004; Prazdny, 1984; Prazdny, 1986; Wilson & Wilkinson, 1998; Wilson & Wilkinson, 2003; Wilson et al., 1997; Wilson, Switkes, & De Valois, 2004). We used concentric Glass patterns, in which the pairs of dots are tangent to the circle at that radius (see Dakin & Bex, 2002; McGraw et al., 2004; Wilson & Wilkinson, 1998). To measure sensitivity to these patterns, we used a structure-in-noise task, in which the dot pairs are presented in a field of random noise. An individual's form coherence threshold is calculated by finding the lowest proportion of paired dots necessary for the participant to discriminate the two patterns and to correctly identify which of them contains the structure (Maloney, Mitchison, & Barlow, 1987). High coherence thresholds are indicative of reduced sensitivity to global form.

1.3. Biological motion

Human observers are sensitive to both local (Troje & Westhoff, 2006) and global (Beintema & Lappe, 2002; Shiffrar, Lichtey, & Heptulla, 1997) motion cues, as well as dynamic form cues (e.g. Beintema & Lappe, 2002) contained in biological motion displays. In the present study, we measured children's thresholds for detecting a point-light human figure upon which was superimposed a number of noise dots derived from phase-scrambled biological motion. Because the motion of the noise dots was identical to the local motion in the target figure, increasing the density of the noise dots forced viewers to rely more and more heavily on global processing mechanisms in order to detect the presence of the target figure; as a result, superior processing of biological motion on this task was associated with greater tolerance for noise. Functional neuroimaging studies strongly implicate the STS in this type of global processing. Thus, biological motion displays depicting a coherent, upright figure result in stronger activation within the STS than displays comprised of scrambled targets (Grossman & Blake, 2001).

2. Summary

A key objective of the present study was to compare sensitivity to cues signalling global motion, global form, and biological motion in a sample of children born very prematurely (at <32 weeks gestation). We also sought to compare the preterm children's performance on each task to that of full-term children who were well matched to the clinical sample on several important demographic variables. In light of past research, we expected to find that preterm children would be impaired, relative to full-term peers, on all three tasks of global processing, but that deficits might be most evident on the tasks involving dynamic stimuli. Data collected from the healthy, full-term children also allowed us to explore the normal development of these processes, relative to one another.

3. Method

3.1. Participants

Participants in this study included a group of 23, five- to nine-year-old preterm children born at <32 weeks gestation, and an age-matched group of 20 full-term control children. Demographic information about the participating children is provided in Table 1. The research protocol was approved by the Human Research Ethics Boards at the University of Manitoba, and informed parental consent was obtained for all participating children.

Preterm children were recruited through the Newborn Follow-Up Programs at Children's Hospital (Health Sciences Centre) and at St. Boniface Hospital, both in Winnipeg, MB. With parental consent, information regarding relevant medical variables was obtained for children in the preterm sample from both of these centres. The information gathered included: birthweight, gestational age, Apgar scores (at 1 and 5 min), duration of mechanical ventilation (days), the results of neonatal cranial ultrasound and other available brain imaging scans, and information regarding whether or not the child had a history of retinopathy of prematurity, bronchopulmonary dysplasia, or sepsis. Preterm children were excluded if they (a) suffered from a major sensory impairment (e.g., blindness, deafness) that would have interfered with testing; (b) were born small-for-gestational-age (birthweight < 3rd percentile), and/or (c) had undergone ventriculo-peritoneal shunting for posthemorrhagic hydrocephalus. The latter two restrictions were put in place to avoid confounding the effects of premature birth with the effects of fetal growth restric-

Table 1
Demographic variables of preterm and full-term sample.

	Full-term control children	Preterm children
Gender distribution	10F:10M	12F:11M
Age-at-test (years:months)	7:3 (SD 12.7 months), range 5:5–8:8	7:3 (SD 15 months), range 5:2–9:1
Gestational age (weeks)	Inclusion criteria specified a range of 38–42	29 (SD 2), range 26–31
Birthweight (g)	3611 (SD 499), range 2722–4451	1224 (SD 205), range 825–1585
PPVT-III (standard score)[a]	112.25 (SD 12.6), range 85–128	106.5 (SD 11.5), range 91–135
Maternal education (mode)	Completed some post-secondary training	Completed post-secondary degree/diploma
Paternal education (mode)	Completed post-secondary degree/diploma	Completed post-secondary degree/diploma
Family income (mode)	Over CAD $75,000	Over CAD $75,000

[a] Age-corrected standard scores on the Peabody Picture Vocabulary Test, 3rd edition were used to estimate verbal intelligence; see Section 3.2.2 and Section 4 for further details.

tion or shunting. Children were also excluded if they had not undergone a minimum of two cranial ultrasound scans in the first 6 weeks of life to document the presence/severity of PVBI. This restriction was put in place because the likelihood of detecting abnormalities is greater with serial scans than with a single scan, and because we planned to compare the performance of preterm children with and without ultrasound-based evidence of PVBI. While structural or quantitative magnetic resonance imaging, and/or diffusion tensor imaging would have provided more sensitive measures of neurological damage (e.g., Anderson et al., 2004; Cooke, 1999; Counsell et al., 2003; Goto et al., 1994; Hintz et al., 2007; Maalouf et al., 2001), the preterm children who participated in the present study were not routinely scanned using these more sophisticated techniques.

Full-term control children, born without medical complication and having no history of developmental problems, were recruited through elementary schools and daycare centres in the community via recruitment letters, posters, and word-of-mouth.

3.2. Demographic and screening measures

3.2.1. General information questionnaire

A parent of each participating child completed a questionnaire designed to provide demographic information. This was deemed necessary in order to determine whether demographic variables such as parental education or family income contributed to the participants' performance on the measures, as these factors have been found to be related to cognitive development in preterm children in other research (e.g., Sommerfelt, Ellertsen, & Markestad, 1995).

3.2.2. Intellectual screening

Verbal intelligence was estimated using the Peabody Picture Vocabulary Test—Third Edition (PPVT-III; Dunn & Dunn, 1997). Performance was measured by comparison with published norms based on a standardization sample of other children in the same age group, with test results being expressed as standard scores (M = 100, SD = 15). This test was used as a control measure to ensure that any difficulties observed in our preterm sample on the experimental tests were not attributable to the presence of a general cognitive delay that would also affect verbal functioning. We controlled for verbal intelligence rather than Performance IQ because tests of Performance IQ rely on visuospatial, visual perceptual and psychomotor skills that depend on neural systems implicated in our experimental tasks. Controlling for Performance IQ differences, then, might specifically limit our ability to detect group differences in performance on our experimental tasks.

3.2.3. Linear acuity

Linear acuity was measured using the *Lighthouse Acuity Chart* (Lighthouse International, New York, NY) for children 7 years of age or over, and using the *Goodlite Crowding Cards* (Good-Lite Company, Chicago, IL) for 5- and 6-year-old children. Different charts were used for the two age groups because we find that younger children are often confused by the number of letters on the Lighthouse chart; the Good-Lite test is a simpler, matching task that induces crowding of the target letters by surrounding them with bars rather than other letters. In order to pass the Lighthouse, children were required to demonstrate 20/20 acuity. In order to pass the Goodlite, 5-year-old children were required to demonstrate 20/25 acuity, while the criterion for 6-year-old children was 20/20 acuity. The choice of these cut-offs was based on clinical experience and the results of earlier studies (e.g., Bowering, Maurer, Lewis, & Brent, 1993).

3.2.4. Binocular fusion: Worth 4-dot test (Richmond Products, Albuquerque, NM)

In this test of binocular fusion, the child wore glasses with a red filter over one eye and a green filter over the other and was shown a flashlight with 1 red dot, 2 green dots, and 1 white dot. The child was asked to report how many dots he/she saw and their colours. Children with normal binocular fusion report seeing 4 dots. Any other responses on this test are indicative of problems with binocular fusion.

3.2.5. Stereoacuity: Titmus test of stereoacuity (Stereo Optical Company, Chicago, IL)

In this test of depth perception, the child wore polarizing lenses and, for various rows of circles and animals, pointed to the one that "jumped out" (the image that looked as though it was floating just above the page as opposed to lying flat on the page). To pass this screening test, 5-year-old children were required to show a stereoacuity of at least 100 arc sec (3/3 animals correct and 5/9 circles correct), while 6–9-year-old children were required to show a stereoacuity of 40 arc sec (3/3 animals correct and 9/9 circles correct). As with the tests of linear acuity, the choice of cut-offs for this test of stereoacuity was based on clinical experience and the results of earlier studies (e.g., Bowering et al., 1993).

3.3. Experimental materials

All experimental tasks were run on a MacIntosh Mini computer. Stimuli were displayed on an Optiquest Q71 monitor (24° high by 32° wide), with a vertical refresh rate of 75 Hz and a screen resolution of 832 × 624 pixels.

3.3.1. Global motion coherence stimuli

Stimuli for the test of sensitivity to global motion coherence were supplied by the Visual Development Laboratory at McMaster University. The stimuli consisted of limited lifetime, random dot kinematograms that included an array of 300 black dots (mean luminance of each dot 4 cd/m^2) presented against a white background (luminance 60.32 cd/m^2). The dots had a diameter of 30 arc min. Each display consisted of 20 frames (each lasting 13 ms), resulting in a dot speed of 18°/s. On any given trial, a certain percentage of the dots (signal) moved coherently among an array of randomly displaced dots (noise). In each successive frame, all signal dots were displaced in the same direction by 0.25°, giving the perception of continuous motion.

3.3.2. Global form coherence (Glass pattern) stimuli

The Glass pattern stimuli were identical to those used in Lewis et al. (2004). They consisted of white dots presented against a grey background (luminance 30 cd/m^2). Each dot was 1.8 min on each side when viewed from the testing distance of 57 cm. Signal dots consisted of pairs of dots placed so as to form a concentric pattern of swirls. The separation between members of each pair of dots was 16.2 min of arc and the mean dot spacing overall was 7.9 min of arc, less than half the spacing between members of a pair. This arrangement ensured that the perception of global structure was not based on local cues regarding dot spacing. Signal patterns were degraded to varying degrees by replacing a percentage of the signal dot pairs with an equal number of randomly spaced noise dots that were the same size and shape as the signal dots. To measure sensitivity to global structure in Glass patterns, subjects discriminated signal patterns from noise patterns (see below). Noise patterns contained the same percentages of dot pairs as the signal patterns, except that each noise dot pair was plotted at a random orientation, thus providing no global shape cues. The remaining dots in each noise pattern were randomly positioned. Thus, noise patterns contained the same percentages of dot pairs and random single dots as the signal patterns but lacked global structure (Wilson & Wilkinson, 1998; Wilson et al., 1997). Accordingly, only global structure could be used as a cue for discrimination.

3.3.3. Biological motion stimuli

The biological motion stimuli were identical to those described in Freire, Lewis, Maurer, and Blake (2006). They consisted of dynamic point-light displays of an adult engaged in a variety of activities (e.g., throwing, climbing, jumping). These displays were generated in Matlab, using the Psychophysics Toolbox extensions (Brainard, 1997). The displays included a total of 25 biological motion animations, and 25 phase-scrambled animations (created by scrambling the temporal phase of the dots comprising each biological motion animation). These animations were used in a familiarization task and in a detection task, which are described below. In the detection task, masking dots comprised of scrambled biological motion were added to the display. In all animations, black dots subtending approximately 10 arc min at a viewing distance of 57 cm appeared against a grey background (luminance 57.7 cd/m^2).

Each animation was displayed for 1 s, which yielded an average speed of approximately 4°/s within each sequence.

3.4. Procedures

Each child was tested individually. Before testing began, the procedures were explained and parental consent for participation was obtained. Parents completed the background information form while the child was in the testing session. Testing for 5- and 6-year-olds was split into two, one-hour sessions run on separate days in order to prevent fatigue. Older children (7–9-year-olds) were tested in a single two-hour session, with rest breaks provided.

Prior to administration of the experimental tests, linear acuity was assessed monocularly at 3 m (Good-Lite Acuity Chart) or at 4 m (Lighthouse Acuity Chart). Testing of each eye was repeated with a +3 dioptre add over the eye to rule out hypermetropia greater than 3 dioptres. This was followed by administration of the Titmus test of Steroacuity and the Worth 4-dot test of fusion. Once the visual screening was complete, the PPVT-III was administered. The order in which the three experimental tests were administered was counterbalanced. During these tasks, the children provided verbal responses that were then entered into the computer by the experimenter, who was unable to see the stimulus displays. During testing the experimenter ensured that the child maintained fixation on the screen, and provided encouragement and praise for continued effort.

3.4.1. Global motion

Prior to beginning the global motion coherence test, participants were given instructions, demonstration trials, and a practice staircase under binocular viewing conditions. These steps were included to ensure that the child understood the task and knew how to perform the task when it became more difficult as a result of the addition of noise dots. The demonstration trials consisted of four trials, two at 100% coherence and two at 50% coherence. The demonstration trials were followed by two practice trials at each of these same two levels of coherence; during these trials the child was asked to specify the direction of perceived motion, with feedback on accuracy being given after each response. The instructions for this task were as follows: "You will see a bunch of dots on the screen that will be moving either up or down. At first all the dots will be moving in the same direction, but soon there will be other dots trying to fool you. Your job is to tell me if most of the dots are moving up (experimenter points up) or down (experimenter points down)." Global motion coherence thresholds were measured using a 2-down, 1-up staircase procedure (Ellemberg et al., 2002; Levitt, 1971). In this procedure, the dot coherence decreased after two successive correct responses, and increased after every incorrect response. The first decrease involved a step size of half an octave (from 100% to 50% coherence), and thereafter reversals changed by a step size of one quarter octave (where 1 octave is a halving or a doubling of a value). After the first reversal, testing continued until eight reversals were completed. Coherence thresholds were measured using the mean coherence of the last six reversals. Feedback was provided after each trial through presentation of a *happy face* or a *neutral/sad face* on the screen following correct and incorrect responses, respectively. After completing a practice staircase, the child completed a second staircase under the same conditions as the practice staircase. The analyses are based on the threshold obtained in the second staircase.

3.4.2. Global form

Prior to beginning global form coherence testing, participants were given instructions, followed by demonstration, criterion, and practice trials. The demonstration trials consisted of four trials depicting (in order) 100% signal, a noise pattern, 75% signal, and a second noise pattern. The instructions were as follows: "You are going to see a circle filled with dots and it is your job to tell me if the dots look all messy (experimenter moved finger in random directions in front of the computer screen) or if you see swirls (experimenter drew imaginary circles in front of the computer screen)". Criterion testing included eight noise and eight 60% signal trials (presented in random order), with criterion to pass being four consecutive correct responses with feedback. Practice trials included eight trials during which four signal values (60%, 40%, 25%, and 10%) were each presented twice in random order. A two-alternative temporal forced-choice procedure was employed, in which the signal appeared randomly in interval 1 or 2 across trials. The child was required to indicate which of the two presentations held the signal (swirls). The percent signal was varied across trials, and thresholds in the practice phase were defined as the percent signal necessary to obtain 75% correct responses. Feedback for errors was provided in this initial practice session.

Although feedback was not provided during the testing session, the children continued to receive encouragement from the experimenter during this phase of testing. Testing was conducted in a similar manner to the practice trials, with four signal values each being presented 20 times, in random order. The choice of signal values used in the test phase with a given child was based on that child's performance during the practice phase. Specifically, children whose thresholds on the practice run were >40%, were tested with the following signal values: 40%, 60%, 80%, and 100%. Those with practice run thresholds of 15–40% were tested with signal values of 10%, 25%, 40%, and 60%. Those with practice run thresholds of <15%, were tested with signal values of 5%, 15%, 30%, and 60%. As in the practice phase, the percent signal was varied across trials, and thresholds were defined as the percent signal necessary to obtain 75% correct responses.

3.4.3. Biological motion

Two tests of biological motion perception were administered. First, a *familiarization task* was administered to assess children's ability to discriminate between a coherent point-light figure (i.e., one whose global shape was consistent with a human form) and a phase-scrambled figure (in which the global shape was disrupted). Second, a *detection task* was administered to assess sensitivity to biological motion.

Prior to beginning the familiarization task, each participant was given instructions, as well as demonstration and criterion trials. First, the child was told that he or she would see patterns of dots moving on the screen for a brief period, and that some of the patterns would look like a person doing something while others would not look like a person. Children were then shown two demonstration trials, one depicting a coherent point-light figure and the other a phase-scrambled point-light display. Following this, they were told to say "yes" if they saw a person and "no" if the moving dots did not look like a person. Criterion testing included presentation of single animations in random order until the child obtained four consecutive correct responses. The familiarization task included 25 coherent and 25 phase-scrambled stimuli, sampled randomly with replacement from the biological motion and scrambled stimulus pools.

In the detection task, the child was also required to say "yes" or "no" after each display to indicate whether a person was present. In this task, however, masking dots comprised of scrambled biological motion were added to the display. As noted in the introduction, as the density of such a mask increases, viewers are forced to rely more and more heavily on global mechanisms for processing biological motion in order to detect the target. Thus, high tolerance to density of noise on this task is indicative of superior global processing of biological motion cues. Children were told that the task would be like "looking for a person in the snow." During the detection task they were also told that initially there would only be a small number of extra dots but that later there would be many more extra dots, making it more difficult to decide whether or not there was a person in each display. Demonstration and criterion trials were the same as those that preceded the familiarization task, with the exception that six masking dots were added to each display. Note that the biological motion task is a detection task, whereas the global motion and global form tasks involve discriminations between two directions or two intervals, respectively.

In the detection task, each child completed two staircases with a short break after completion of the first. No practice staircase was administered. A 2-up, 1-down staircase procedure was used, in which two successive correct responses were required for an increase in the number of noise dots, and one incorrect response resulted in a decrease in the number of noise dots. The first display did not include any noise dots. For the first 12 reversals, six masking dots were added or removed on a given trial. After this, the number of masking dots added or removed was reduced to 3, in order to obtain a more precise estimate of the child's threshold. Testing continued until 36 reversals were complete. Detection thresholds were measured using the mean thresholds for the last 10 reversals in each staircase. The thresholds from the two staircases were averaged for each child.

4. Results

4.1. Demographic and screening measures

As can be seen from Table 1, the samples of preterm and full-term children were quite comparable to each other in terms of gender distribution, age-at-test, estimated verbal intelligence, parental education and family income. However, because we were interested in exploring developmental differences within and across the groups on these tasks, in the analyses described below the children in each sample were divided into two age groups: a group comprised of children aged 5:0–6:11 years, and a group comprised of children 7:0–9:1 years. Separate analysis of variance (ANOVA) tests confirmed that, within each age group, children in the preterm and full-term samples were matched in terms of *age-at-testing*: $F(1,17) = 0.90$, $p = 0.36$ for the 5–6-year-old group, and $F(1,22) = 0.01$, $p = 0.95$ for the 7–9-year-old group. In addition, all four groups of children were found to be comparable to one another in terms of their *verbal intelligence*, as estimated by age-corrected standard scores on the PPVT-III, $F(3,39) = 1.18$, $p = 0.33$. Moreover, a series of Kruskal–Wallis tests revealed that the four groups were also comparable to one another in terms of gender distribution [$\chi^2(3) = 3.21$, $p = 0.36$], paternal education [$\chi^2(3) = 0.26$, $p = 0.97$], maternal education [$\chi^2(3) = 6.05$, $p = 0.11$], and household income [$\chi^2(3) = 2.153$, $p = 0.54$]. Because the four groups were comparable on the measures mentioned above, and because threshold scores on the three experimental tests were not significantly correlated with PPVT-III

Table 2
Summary of medical history variables, results of the Titmus test of stereoacuity, and deficit scores for the three experimental tests, for each child in the preterm sample.

ID	AGE	GA	BW	PVBI	ROP	BPD	Sepsis	Stereo	GF	BM	GM
1	82	28	1132	POR-CYS	n	N	n	Fail	0.41	1.50	0.27
2	88	31	1411	POR-CYS	Y	N	n	Fail	0.53	1.14	1.60
3	88	31	1425	IVH	n	N	Y	Pass	0.81	0.71	0.24
4	91	31	1346	IVH	n	Y	n	Fail	0.92	1.21	1.10
5	88	27	1225	IVH	Y	N	n	Pass	0.93	1.48	0.40
6	102	30	1410	n	n	N	n	Pass	1.10	1.10	0.97
7	107	28	1098	PVL	n	N	n	Fail	1.82	1.54	0.23
8	108	27	864	n	Y	N	n	Fail	**2.29**[a]	1.10	1.47
9	76	30	1356	IVH	Y	N	Y	Fail	1.23	1.81	0.41
10	102	30	1585	n	n	Y	Y	Pass	0.77	1.81	1.13
11	104	27	1030	IVH	Y	N	Y	Pass	–	1.88	–
12	62	28	1333	n	n	N	n	Pass	1.38	1.98	1.54
13	71	27	1188	IVH/PVL	Y	N	Y	Fail	1.57	**2.86**[a]	0.34
14	109	27	1090	IVH	n	N	n	Fail	1.52	1.18	**2.00**[a]
15	88	31	1541	POR-CYS	Y	N	Y	Pass	0.54	1.44	**2.36**[a]
16	96	31	1451	n	n	N	n	Fail	0.91	1.05	**2.54**[a]
17	83	28	1120	n	n	N	n	Pass	1.47	0.82	**2.79**[a]
18	84	27	944	n	Y	Y	n	Pass	0.89	1.01	**2.84**[a]
19	82	26	825	n	Y	N	n	Fail	1.43	1.07	**5.04**[a]
20	71	27	1223	IVH	Y	N	n	Pass	1.99	1.87	**2.61**[a]
21	106	28	1133	n	n	Y	n	Fail	**3.45**[a]	**2.11**[a]	0.91
22	62	28	1104	n	Y	N	Y	Fail	1.30	**2.72**[a]	**2.54**[a]
23	66	29	1327	n	n	N	Y	Fail	0.93	**3.49**[a]	**2.71**[a]

Age: age-at-testing (months); GA: gestational age (weeks); BW: birth weight (g); PVBI: periventricular brain injury, including porencephalic cysts (POR-CYS), intraventricular hemorrhage (IVH), and periventricular leukomalacia (PVL); ROP: retinopathy of prematurity; BPD: bronchopulmonary dysplasia; stereo: Titmus test of stereoacuity; n: negative history; Y: positive history. Note that deficit scores could not be computed for case 11 for the global form or global motion tasks due to missing data.

[a] Impairment as defined by a deficit score of ≥2.

scores and showed no relationship to any of the demographic variables ($p > 0.21$ in all cases), subsequent analyses did not control for these variables.

4.1.1. Visual screening tests

All control children passed all subtests of the visual screening battery. In contrast, while all of the 23 preterm children passed the tests of visual acuity and binocular fusion and none were found to have amblyopia, 13 children in the preterm sample (56%) failed the test of stereoacuity (see Table 2).

4.2. Sensitivity to global motion, global form, and biological motion

Coherence thresholds for global motion and global form were entered into separate ANOVA tests, each with two grouping variables: Group (full-term, preterm) and Age (5–6 years, 7–9 years). In both analyses there was a significant main effect for Group: $F(1,38) = 4.32$, $p < 0.05$ for global motion coherence, and $F(1,38) = 4.09$, $p < 0.05$ for global form coherence. Examination of mean scores revealed that preterm children exhibited higher coherence thresholds (lower sensitivity) than full-term control children for both global motion and global form (see Figs. 1 and 2). A significant main effect of Age was also observed in each analysis [$F(1,38) = 10.22$, $p < 0.01$ for global motion, and $F(1,38) = 11.99$, $p < 0.01$ for global form], with 7–9-year-old children exhibiting superior performance overall. The Group × Age interaction was not significant in either analysis.

Data from the tests of biological motion perception (i.e., accuracy scores for the familiarization task and noise tolerance for the detection task) were entered into two separate ANOVA tests, each with two grouping variables: Group (full-term, preterm), and Age (5–6 years, 7–9 years). Analysis of the data from the familiarization task revealed that children in the preterm and full-term groups did not differ in terms of their ability to discriminate an unmasked, coherent point-light figure from a scrambled display (see Fig. 3a). There was also no difference in performance between 5–6-year-old and 7–9-year-old children on this task. The results from the detection task, however, followed a rather different pattern (see Fig. 3b). Here, a significant main effect of Group was observed, $F(1,39) = 17.80$, $p < 0.01$, whereby children in the preterm group exhibited less tol-

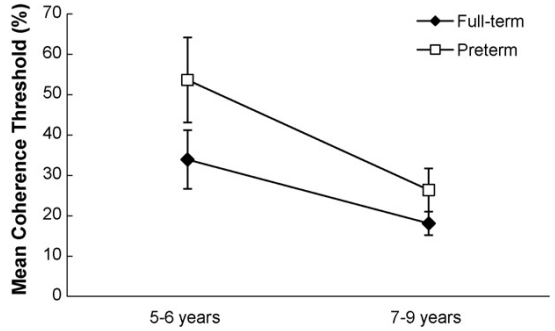

Fig. 1. Mean global motion coherence thresholds (error bars represent SE of mean values) showing a main effect of Group (preterm vs. full-term) and Age (5–6 years vs. 7–9 years). Lower scores on this task reflect better sensitivity.

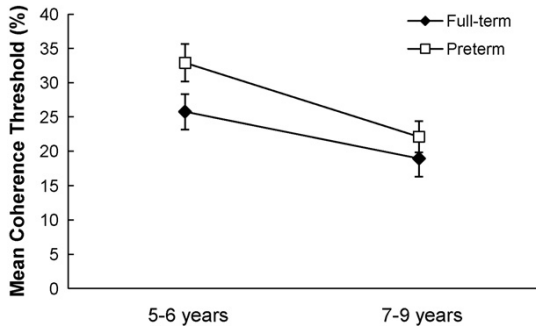

Fig. 2. Mean global form coherence thresholds (error bars represent SE of mean values) showing a main effect of Group (preterm vs. full-term) and Age (5–6 years vs. 7–9 years). Lower scores on this task reflect better sensitivity.

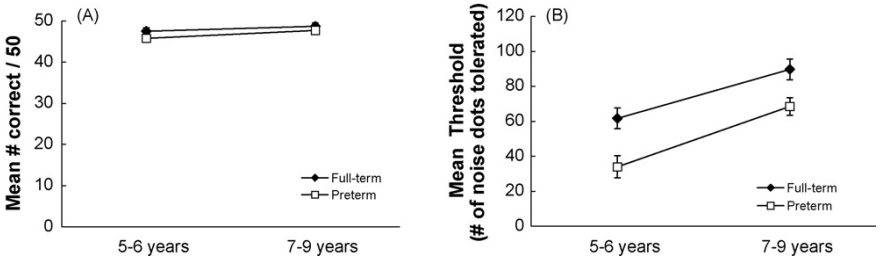

Fig. 3. (a) Mean accuracy (number correct out of a possible maximum score of 50) on the biological motion familiarization task (error bars represent SE of mean values). All groups showed ceiling-level performance. (b) Mean biological motion thresholds showing a main effect of Group (preterm vs. full-term) and Age (5–6 years vs. 7–9 years) (error bars represent SE of mean values). Higher scores on this task reflect better sensitivity.

erance to noise (i.e., reduced sensitivity to biological motion) than children in the full-term group. There was also a significant main effect of Age in this analysis, $F(1,39) = 29.01$, $p < 0.01$; examination of group means showed that sensitivity to the presence of the dynamic figure improved with age. The Group × Age interaction was not significant in either analysis.

4.3. Correlations between experimental measures

To examine relationships between performance on the experimental tasks, we computed pairwise correlations between the three threshold scores. These correlations were computed for full-term and preterm children, separately. After controlling for age, no significant pairwise correlations emerged among the threshold scores, for either group of children.

4.4. Effect sizes and deficit scores

As noted above, a main effect of Group was observed for each of the threshold measures. Effect sizes were calculated using Cohen's *d* (Cohen, 1988) to determine the magnitude of the impairments seen in our preterm sample, relative to our full-term sample. Effect sizes of 0.61, 0.39, and 0.33 were found for global motion coherence, biological motion, and global form coherence, respectively. These values represent medium-to-large (global motion), and small-to-medium (biological motion, global form) effect sizes (Cohen, 1988; although see Fern & Monroe, 1996).

While calculation of effect sizes is important and informative, these measures do not allow us to compare the magnitude of preterm children's impairments directly, across the three tasks. To do this, we needed to convert the threshold scores to a common metric. This was done using a two-step procedure. First, we matched each preterm child to the three full-term controls who were closest to that child in age. [The average difference between the age of a given preterm child and the mean age of his/her three matched controls at the time of testing was 0.35 months (i.e., 1.5 weeks); a paired samples *t*-test confirmed that these values were not significantly different, $t(22) = 0.66$, $p > 0.50$.] Next, we calculated a *deficit score* for each measure. In the case of the global motion and global form scores, this was accomplished by dividing each preterm child's coherence threshold on a given task by the mean threshold of his/her three age-matched controls on that same task. Because low (rather than high) scores on the biological motion task were indicative of worse performance, the opposite ratio was computed for this task. In each case, a deficit score of 1 indicates that the preterm child performed the task at a level exactly comparable to that of the control children, while a score greater than 1 indicates some level of impairment. Because the control group was too small to define abnormalities in performance based on percentiles in the typical population, we defined an *impairment* as a deficit score of ≥2. Although this criterion was arbitrary, no child in the control group would have been defined as having had an impairment on any task by this criterion. Deficit scores for each preterm child in the sample are presented in Table 2, along with information about relevant medical variables and performance on the Titmus test.

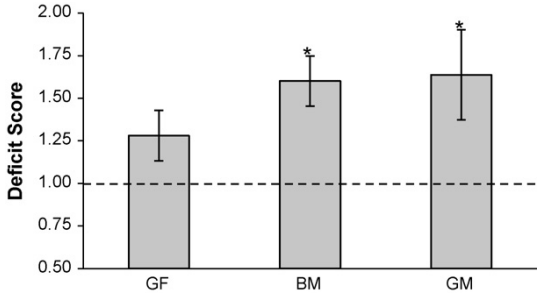

Fig. 4. Mean deficit scores for preterm children (error bars represent SE of mean values). Mean deficits scores were significantly greater than 1 for biological motion detection and global motion coherence, indicating a statistically significant deficit.

Deficit scores were entered into an ANOVA with one grouping variable, Age (5–6 years, 7–9 years), and one repeated measure, Task (global motion, global form, biological motion). Deficit scores were smaller for 7–9-year-old than for 5–6-year-old preterm children, $F(1,38) = 10.22$, $p < 0.01$. Neither the main effect of Task nor the Age × Task interaction was significant. However, a series of planned, one-sample *t*-tests comparing the mean deficit score on each test to a value of 1 (i.e., "no impairment") revealed that, while the mean deficit score for the global form task was not significantly different from 1 [$t(22) = 1.93$, $p > 0.06$], the mean deficit scores on the two remaining tasks were significantly greater than 1 [biological motion, $t(22) = 4.18$, $p < 0.01$; global motion, $t(21) = 2.47$, $p < 0.03$] (see Fig. 4).

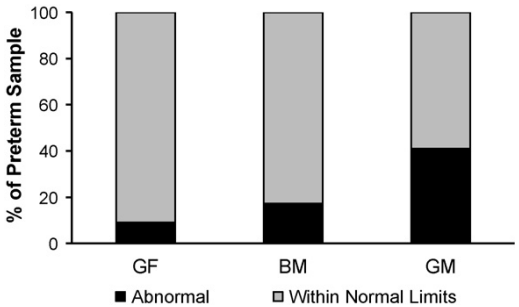

Fig. 5. Percentage of children showing abnormal performance (i.e., an impairment denoted by a deficit score ≥2) for each threshold measure. GF: global form; BM: biological motion; GM: global motion.

Just over half of the preterm children (12 of 23) had deficits scores large enough to indicate an impairment in performance (≥2, i.e., at least one octave) for one or more of the three experimental tasks. As can be seen in Fig. 5, 9% of the sample showed impairment on the global form task, compared to 17% on the biological motion task and 41% on the global motion task. Using a Friedman test, we determined that these proportions were not equivalent, $\chi^2(2) = 6.50$, $p < 0.04$. Follow-up pairwise Wilcoxon tests confirmed that impairment was much more common in global motion perception than in global form perception ($Z = -2.11$, $p < 0.04$). Indeed, on the global motion task the proportion of children exhibiting impairment was equivalent to the proportion who performed within normal limits, $\chi^2(1) = 0.73$, $p > 0.3$. Rates of impairment with biological motion perception fell at an intermediate level, not differing significantly from those seen with either of the other two tasks. It is interesting to note, however, that if one were to include 'borderline' cases (those with deficit scores ≥1.8), the rates of impairment on the biological motion and global motion tasks would be almost identical to one another (at 40% and 41%, respectively) and more than twice as high as those seen on the global form task (at 18%).

As can be seen in Table 2, no preterm child showed impairment across all three tasks (although the deficit scores of case 20 were all ≥1.87, indicating borderline or worse performance across the board). Interestingly, the majority of children with impairments (9 of 13 or 69%) exhibited difficulties with only one test; in the vast majority of these cases (7 of 9 or 78%) impairments were seen on the global motion task. When multiple impairments were observed, they were seen either in the global form and biological motion tasks (case 21), or in the biological motion and global motion tasks (cases 22 and 23). No child showed impairments in global form and global motion processing, with preserved sensitivity to biological motion. In addition, no significant correlations were observed between any of the three deficit ratios ($p > 0.45$ in all cases). Together, these results provide support for the idea that these three forms of visual processing involve different neural mechanisms.

4.5. Age-related changes

Effect sizes were computed for the difference in threshold scores between 5–6-year-old and 7–9-year-old children in both the preterm and full-term samples, for each task. For global motion coherence, the effect sizes for age were calculated at $d = 1.62$ and $d = 1.70$ for the preterm and full-term groups, respectively. The corresponding effect sizes for global form coherence were calculated at $d = 1.32$ and $d = 0.83$, respectively, while those for biological motion detection were $d = 1.84$ and $d = 1.49$, respectively. All of these values represent large effects (Cohen, 1988). Although this is cross-sectional data, these results would seem to suggest that performance on each of the tasks may improve over time, even among preterm children. It is important to note, however, that when preterm children's deficit scores (which provide an index of the magnitude of impairment relative to age-matched controls) were correlated with age, only deficits in biological motion appeared to diminish with increasing age [$r(21) = -.51$, $p = 0.01$]. Age was not significantly correlated with deficit scores seen in either the global motion [$r(20) = -.25$, $p = 0.27$] or global form [$r(20) = .25$, $p = 0.26$] task.

4.6. The relationship between experimental measures and medical variables

For preterm children, correlations controlling for age (in months) were computed between each of the threshold and deficit scores and each of the following continuous medical variables: birthweight, gestational age, Apgar at 1 min, Apgar at 5 min, days on supplemental oxygen, and days on mechanical ventilation. Some caution should be exercised in interpreting the results of these analyses given both the large number of correlations that were examined, and the possibility that restriction in range may have been a factor with some of the medical variables. Having said that, the only significant relationships that were observed were those between performance on the global form test and select medical variables. Specifically, the preterm children who performed most poorly on the global form perception test (obtaining relatively high coherence thresholds and large deficit scores) were those who had lower birthweights and who had spent more days on mechanical ventilation or supplemental oxygen. [Correlations with threshold scores: birthweight, $r(18) = -0.53$, $p < 0.05$; days on mechanical ventilation, $r(18) = 0.49$, $p < 0.05$; days on supplemental oxygen, $r(18) = 0.51$, $p < 0.05$. Correlations with deficit scores: birthweight, $r(20) = -0.48$, $p < 0.05$; days on mechanical ventilation, $r(20) = 0.64$, $p < 0.01$; days on supplemental oxygen, $r(20) = 0.65$, $p < 0.01$].

The impact of several dichotomous medical variables [i.e., history of PVBI documented with ultrasound (positive/negative), history of retinopathy of prematurity (positive/negative); performance on the Titmus test of stereoacuity (pass/fail)] on threshold and deficit scores for each of the experimental measures was also investigated through a series of one-way analysis of covariance tests which controlled for participants' age. None of these medical variables was related to outcome in the preterm sample.

5. Discussion

This study is the first to examine differential vulnerability of systems supporting the perception of global form, global motion, and biological motion in preterm children. Relative to full-term controls, preterm children in the present sample showed reduced sensitivity to all three types of stimuli but, as expected, these deficits were not comparable in magnitude. Thus our deficit score analysis revealed that problems with the processing of dynamic cues – particularly those signalling coherent global motion but also, to a lesser extent, those signalling the presence of dynamic forms in biological motion displays – were more striking than those seen with the processing of static form cues. Indeed, rates of impairment were almost twice as high for the biological motion task, and four times as high for the global motion task, as for the global form test.

Our finding that deficits in global motion coherence were more common and severe than deficits in global form perception is consistent with the results of Atkinson and Braddick (2007). They found that while approximately 22% of 6–7-year-old preterm children scored below the 5th percentile on their test of global motion perception, only approximately 5% scored below this cut-off on their test of global form perception. They concluded, on this basis, that the dorsal stream is particularly vulnerable to damage or atypical development in preterm children. Dorsal stream vulnerability has also been documented in children with a range of neurodevelopmental disorders including autism (Spencer et al., 2000; Villalobos, Mizuno, Dahl, Kemmotsu, & Müller, 2005), developmental dyslexia (Cornelissen, Richardson, Mason, Fowler, & Stein, 1995; Hansen, Stein, Orde, Winter, & Talcott, 2001; Ridder, Borsting, & Banton, 2001), and Williams' Syndrome (Atkinson et al., 2001; Atkinson et al., 2003; Atkinson et al., 2006; Atkinson et al., 1997).

The high rate of impairment that we observed in our global motion task is consistent with results of an earlier study from our laboratory that also involved 5–9-year-old children (MacKay et al., 2005). In that study, however, the mean deficit ratio for global motion (M = 6.7) was much larger than that reported here (M = 1.6). A number of factors likely account for this difference. First, in the present study we used a new set of stimuli in which both the signal and the noise dots (rather than only the noise dots) had a limited lifetime. The new stimuli appeared to be more challenging for both

preterm and full-term participants than those used in our earlier research, but the difference between children's performance in the two studies was more marked in the full-term than in the preterm samples. Thus, while full-term children required 14.5% more coherence to reach threshold in the present study compared to in our previous report (i.e., 24.3% vs. 9.8%), preterm children required only 7.4% more coherence to reach this level of performance (37.2% in the present study vs. 29.8% in our previous report). As preterm children's deficits were defined in relation to the scores obtained by full-term controls, this difference would have had a large effect on the magnitude of the deficits measured in the two studies. An additional factor that may have contributed to differences observed between the two studies is that our current method of creating deficit scores, in which each preterm child's score was compared to the mean score of three control children, may have resulted in more conservative estimates than those obtained in the previous study, in which a 1:1 matching approach was adopted.

By examining deficit scores, we were able to identify cases showing qualitatively different patterns of impairment. The fact that some preterm children showed *isolated impairments* in the perception of global form, biological motion, and global motion supports the current view (Peelen et al., 2006; Poom & Olsson, 2002; Servos et al., 2002) that different neural mechanisms are involved in the processing of these three types of visual stimuli. This is also consistent with the observation that threshold scores for each of these stimuli were not correlated with one another when age was controlled for. Of course, *multiple deficits* were also sometimes observed in our preterm sample. Interestingly, however, we did not observe any cases displaying combined deficits in global motion and global form perception with *preserved* biological motion perception. In addition, when *deficits* in biological motion perception were seen these occurred either in isolation (case 13), or in combination with deficits in global form perception (case 21), global motion perception (cases 22 and 23), or both (this pattern was seen in case 20, who showed at least borderline performance in all three tasks). These findings are consistent with observations in adult cases suggesting that impairments in biological motion perception do not follow from damage that is restricted to either motion-processing areas in the dorsal stream, or form-processing areas in the ventral stream (Vaina & Gross, 2004).

5.1. Factors contributing to the deficits in visual perception observed in preterm children

As a group, the preterm children displayed reduced sensitivity to all three types of global cues under study. Despite this, deficits were clearly more marked in some tasks than others. To understand the basis of their problems, we need to examine factors that could have had generalized effects on visual development, as well as those that might account for the differential vulnerability we observed. Our data suggest that none of the difficulties preterm children experienced could be attributed to group differences in general intelligence (as indexed by verbal ability) or demographic variables such as parental education, gender, or household income. The results of the visual screening test also confirmed that they could not be explained by impaired visual acuity or amblyopia. Nor were they related to stereoacuity deficits; thus, although approximately half of the preterm children in this study failed the stereoacuity test, these children did no worse (as a group) than those preterm children who passed the test, on any of the experimental measures.

We have suggested that the difficulties we observed reflect problems with global processing, but it is also important to explore the role that general deficits in visual attention or figure-ground segregation may have played in our results. While we acknowledge that problems with visual attention that have been documented in preterm children (e.g., Foreman et al., 1997; Jakobson et al., 2006) may have contributed to the generally lower sensitivity that we observed for all three types of stimuli, we do not feel that attentional problems can adequately account for the differential vulnerability that was evident, as the attentional demands of the three tasks were quite comparable. Attentional demands were especially well matched for the global motion and global form tasks, where coherence thresholds were being measured.

Like problems with visual attention, problems with figure-ground perception have been documented in some preterm children (e.g., Amicuzii et al., 2006; Kiper, Zesiger, Maeder, Deonna, & Innocenti, 2002). Again, we acknowledge that when such difficulties are present they may contribute to or, in some cases (e.g., children with amblyopia; Wang, Ho, & Giaschi, 2007), be a primary factor underlying difficulties on tasks such as the global form and biological motion tasks used here, in which participants are required to find a static or dynamic form within distracting noise dots. It is not clear, however, how a basic problem with figure-ground perception could fully account for cases exhibiting dramatic impairment in global motion perception with intact global form and biological motion perception (cases 14–19), or for cases showing impairment in either global form (case 8) or biological motion (case 13) but not both.

If the *degree* of prematurity was an important factor in children's performance, we might have expected to find that gestational age and/or birthweight would be strong predictors of impairment in the preterm group. This was only the case with the global form task, and not with the remaining tasks; thus, only global form coherence thresholds and deficit scores on the global form task were significantly correlated with birthweight in the preterm sample. While this might make it appear that the degree of prematurity was only a risk factor for problems with global form processing, this conclusion must be viewed with caution for several reasons. First, in the preterm sample, performance on the global form coherence task was associated not only with birthweight, but also with markers of respiratory difficulty. It may be, then, that medical complications played a more important role than degree of prematurity in determining performance on this task. Second, our sample of preterm children included only three children born weighing less than 1000 g (cases 8, 18, and 19), and only one child was born at a gestational age less than 27 weeks (case 19). It is possible, then, that the failure to demonstrate an association between gestational age or birthweight and performance on the global motion and biological motion tasks reflected a problem with restriction of range in these medical variables. Finally, when we look at the entire sample of preterm and full-term children tested in the present investigation, it is clear that there were large group differences in thresholds obtained on all three tasks, with the larger and later-born full-term children outperforming those in the preterm group. It should not be surprising to learn, then, that birthweight and gestational age were related to performance on all three tasks in the full sample. In future work, efforts should be made to explore these relationships in samples that include more children born extremely prematurely (<25 weeks gestation), and children born only moderately prematurely (32–36 weeks gestation)—a group not represented in the present study.

There are several routes through which the degree of prematurity might, *directly or indirectly*, have contributed to the differential vulnerability we observed. The first has to do with the fact that different visual subsystems follow different developmental trajectories. As noted in the introduction, numerous studies (Atkinson & Braddick, 1992; Braddick et al., 2005; Braddick et al., 1986; Burkhalter et al., 1993; Wattam-Bell, 1991) have highlighted a differential time-course for the development of form- and motion-processing systems in typically developing infants. It may be that these differences create a window in which motion-processing systems are particularly vulnerable to neu-

rodevelopmental or experiential factors operating in the perinatal period.

Another fact that cannot be ignored is that preterm children – particularly those born very early and at very low birthweight – are at substantial risk for neurological damage and/or other insults that affect neurodevelopment. Thus the incidence of both PVBI and (especially) diffuse white matter injury are high in children born very prematurely (e.g., Counsell et al., 2003; Inder, Anderson, Spencer, Wells, & Volpe, 2003; Inder, Wells, et al., 2003; Volpe, 2003). These types of insults show a particular regional distribution, such that areas near the parieto-occipital junction (e.g., parieto-occipital and midtemporal white matter, parieto-occipital grey matter) are more vulnerable to damage than regions located more ventrally (Back et al., 2001; Back et al., 2007; Back & Rivkees, 2004; Goto et al., 1994; Peterson et al., 2003). The regional distribution of this damage, then, might be a key factor underlying the differential vulnerability we observed in problems with the processing of global form, global motion, and dynamic form. Certainly, Pavlova et al. (2006) have argued that the presence and extent of parieto-occipital periventricular leukomalacia (rather than prematurity *per se*) is a strong predictor of preterm adolescents' sensitivity to biological motion. They suggested that damage to this region might have interfered with preterm children's performance on their task by: (a) disrupting a cortical-subcortical network involved in visual binding and spatial attention; (b) disrupting white matter pathways connecting various parts of the distributed cortical network involved in biological motion perception; or (c) disrupting posterior cerebral cortical neuronal development. In our sample of preterm children, there was no clear association between performance on the experimental tasks and the presence of PVBI as documented with neonatal cranial ultrasound. As noted earlier, however, ultrasound measurements simply are not sensitive enough to detect some forms of brain damage in this population (Anderson et al., 2004; Arzoumanian et al., 2003; Hashimoto, Hasegawa, Kida, & Takeuchi, 2001; Inder, Anderson, et al., 2003; Rademaker et al., 2005; Woodward, Anderson, Austin, Howard, & Inder, 2006). This may have compromised our ability to classify children correctly with regard to their neurological status. The use of more sophisticated forms of imaging (e.g., structural or diffusion-based magnetic resonance imaging) might have allowed us to identify subtle forms of damage that contributed to the performance difficulties we observed.

One final point should be made regarding the vulnerability of motion-processing systems in preterm children. We have highlighted, above, the finding that 40% of our sample of preterm children showed rather dramatic problems with global motion perception, but we should also note that more than one-fifth of the sample actually *excelled* in their performance on this task. These children (cases 1, 3, 7, 9 and 13) obtained deficit scores <0.5; to have scored in this range, of course, the preterm child would have required less than half as much coherence in the display (i.e., tolerated twice as much noise) as his/her matched controls. Superior global form perception was also noted in one of these cases (case 1). Interestingly, ultrasound images obtained on all of these children showed evidence of abnormality; these children, then, were clearly not ones who had "escaped" neurological damage. Future studies incorporating other behavioural measures and the use of functional imaging techniques might shed light on how these children achieved such good performance in select areas, relative to their peers. Clearly, it remains a challenge for the "dorsal stream vulnerability" hypothesis to account for these findings.

5.2. Developmental changes in task performance in full-term and preterm children

Although a key objective of the present study was to look for evidence of differential vulnerability to problems with three different types of global processing in our preterm sample, our study design also permitted us to explore developmental changes in performance on all three tasks, in both full-term and preterm children. This allowed us not only to examine normal age-related changes in performance, but also to address the question of whether deficits observed in young preterm children are likely to lessen, remain stable, or be exacerbated over time.

We did not test an adult sample, and thus cannot comment on how our full-term children were performing relative to adults on any of the three tasks. However, across the age-span studied (5:0–9:1 years), we did observe age-related improvement in sensitivity across all measures. These findings are consistent with results from other laboratories showing continued improvement in typically developing children's ability to process biological motion (Freire et al., 2006; Pavlova, Krägeloh-Mann, Sokolov, & Birbaumer, 2000) and global form (Lewis et al., 2004), throughout this age range. These and other findings suggest that the neural systems supporting these abilities continue to develop increased functionality into later childhood. In future investigations, we plan to test older children and adults in order to gain a better appreciation of how sensitivity to the particular stimuli used here changes over time, and when it stabilizes.

As in the case of full-term controls, older preterm children showed better sensitivity to all three types of stimuli than younger preterm children. However, analysis of the threshold scores revealed no significant interactions between Group and Age for any of the experimental measures. Moreover, at least in the case of the global form and global motion tasks, deficit scores were not negatively correlated with participants' age. With these two measures, then, there was little evidence to suggest a pattern of catch-up (i.e., a "closing of the gap"). Nonetheless, "deficits" in global form perception were relatively small. In any case, the fact that sensitivity to global form cues remained low in older preterm children (overall) warrants further study, particularly as relatively little is known about form-processing skills in this population. The large and persisting deficits we observed in global motion perception were not unexpected, particularly as we have shown elsewhere that older preterm children (tested at a mean age of 11 years) exhibit a striking impairment in their ability to process motion-defined forms, a skill which also involves global motion processing (Downie et al., 2003).

Although no relationships were observed between preterm children's age and the magnitude of their deficits in either global form or global motion perception, age was negatively correlated with deficit scores in the biological motion task. This might suggest that the "gap" in performance between full-term and preterm children on this measure will eventually close, but this is not at all certain. Indeed, other researchers have described deficits in biological motion perception in preterm adolescents who experienced periventricular brain damage (Pavlova et al., 2003; Pavlova et al., 2005). It may be that, while performance improves over the age range included in our study, it may exhibit a plateau at some point before adolescence. Alternatively, the children in the present sample may have been less compromised than those studied by Pavlova and colleagues. We hope to recall the children who participated in the current study for additional testing in the future, to explore some of these possibilities.

6. Conclusions

We have shown here that, while global processing (in general) poses a challenge for preterm children, impairments in global form perception are rare. Deficits in the ability to process global motion, on the other hand, affected 40% of our preterm sample. Difficulties in the global analysis of biological motion displays were also apparent, although to a lesser degree. Recent evidence suggests that

distinct portions of the cortical visual system involved in form and motion processing develop at different rates and may be differentially vulnerable to early brain injury or atypical neurodevelopment (see Braddick, Atkinson, & Wattam-Bell, 2003). Given this, it seems likely that the increased vulnerability of motion-processing systems (relative to form processing systems) may be related to: (a) the fact that motion-processing systems are normally undergoing more rapid changes during the perinatal period; and/or (b) the fact that regions of the brain known to be important for different aspects of motion perception are recognized to be particularly vulnerable to diffuse white matter injury and other insults (Back et al., 2001; Goto et al., 1994; Peterson et al., 2003). Further studies with older samples of children born preterm will help to clarify if or how performance in these three areas of visual competence continues to change over the course of adolescence and young adulthood.

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