Fast development of global motion processing in human infants

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Although global motion processing is thought to emerge early in infancy, there is debate regarding the age at which it matures to an adult-like level. In the current study, we address the possibility that the apparent age-related improvement in global motion processing might be secondary to age-related increases in the sensitivity of mechanisms (i.e., local motion detectors) that provide input to global motion mechanisms. To address this, we measured global motion processing by obtaining motion coherence thresholds using stimuli that were equally detectable in terms of contrast across all individuals and ages (3-, 4-, 5-, 6-, and 7-month-olds and adults). For infants, we employed a directional eye movement (DEM) technique. For adults, we employed both DEM and a self-report method. First, contrast sensitivity was obtained for a local task, using a stochastic motion display in which all the dots moved coherently. Contrast sensitivity increased significantly between 3 and 7 months, and between infancy and adulthood. Each subject was then tested on the global motion task with the contrast of the dots set to 2.5 × each individual's contrast threshold. Coherence thresholds were obtained by varying the percentage of coherently moving "signal" versus "noise" dots in the stochastic motion display. Results revealed remarkably stable global motion sensitivity between 3 and 7 months of age, as well as between infancy and adulthood. These results suggest that the mechanisms underlying global motion processing develop to an adult-like state very quickly.

Introduction

Several studies in infants have documented that the ability to discriminate direction of motion emerges by approximately 2 months of age (see Braddick, Atkinson, & Wattam-Bell, 2003, for a review). However, there continues to be debate regarding at what point in development motion mechanisms become adult-like, and whether this differs for the development of "local" versus "global" motion processing. Local motion information is provided by spatiotemporally-correlated changes in light intensity, and can be signaled by individual directionally selective neurons with small receptive fields, like those in area V1. Typically, moving gratings are used to test local motion processing. In contrast, global motion processing is a second-stage computation that integrates local direction signals into a coherent global motion signal. This stage is thought to arise in higher levels of extrastriate cortex with larger receptive fields that can integrate inputs across many local motion detectors, with the most attention paid to the middle temporal area, MT (e.g., Britten, Shadlen, Newsome, & Movshon, 1993; Qian, Andersen, & Adelson, 1994; Rudolph, Ferrera, & Pasternak, 1994; Snowden, Treue, & Andersen, 1992). An example of stimuli used to test global motion processing is plaid patterns, composed of two superimposed gratings moving in different directions. Another stimulus, employed in the current study, is a stochastic motion display wherein a portion of "signal" dots moves in a coherent fashion (e.g., leftward or rightward) and the remaining "noise" dots move in a random fashion (Newsome & Paré, 1988). This stimulus requires integration across space to compute the overall global direction of the dots.

There is evidence for both local and global motion processing abilities in infants, which is not surprising given data from neurophysiological studies in infant monkeys showing that both V1 and MT neurons are

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directionally selective as early as 1 week of age (Chino, Smith, Hatta, & Cheng, 1997; Hatta et al., 1998; Kiorpes & Movshon, 2003b; Movshon, Kiorpes, Cavanaugh, & Hawken, 1999; and reviewed in Kiorpes & Movshon, 2004a, but see Kourtzi, Augath, Logothetis, Movshon, & Kiorpes, 2006, for a more complex view). With respect to *local* motion, it has long been known that young infants possess local motion mechanisms, as evidenced by directionally-appropriate eye movements (DEM) to moving stimuli. Specifically, optokinetic nystagmus (OKN) eye movements in response to moving gratings are seen in newborns (e.g., Hainline, 1984; Kremenitzer, Vaughan, Kurtzberg, & Dowling, 1979; Manny & Fern, 1990; Morrone, Atkinson, Cioni, Braddick, & Fiorentini, 1999; Roy, Lachapelle, & Lepore, 1989). Saccades and smooth pursuit in response to moving targets are seen by 2 months of age (Phillips, Finocchio, Ong, & Fuchs, 1997; Rosander & von Hofsten, 2002; Shea & Aslin, 1990).

Further evidence for local motion mechanisms in infants comes from studies that employ forced-choice preferential looking (FPL), which uses infants' increased looking to one side of a visual display over the other side, to determine if infants can detect or discriminate the presence of any differences between the two sides. Using FPL in a classic summation paradigm, it has been shown that, like adults, the contrast sensitivity of 3-month-old infants is about two-fold higher for moving gratings than counterphase gratings, which is taken as evidence for directional mechanisms for local motion (Dobkins & Teller, 1996a). Other FPL studies using moving dots have shown that infants prefer to look at (and therefore discriminate) displays in which all dots move in one direction over displays in which the dots move in random directions (Atkinson, Hood, Wattam-Bell, & Braddick, 1992; Wattam-Bell, 1996a, 1996b, 1996c). As further evidence for sensitivity to local motion, infants prefer displays that have different directions of motion versus one direction of motion (Banton, Dobkins, & Bertenthal, 2001; Bosworth & Birch, 2005). Corroborating the perceptual studies, neural evidence for the existence of local motion detectors has been provided by studies using visually evoked potential studies in infants (Birch, Fawcett, & Stager, 2000; Bosworth & Birch, 2007; Hamer & Norcia, 1994; Wattam-Bell, 1991).

Evidence for *global* motion processing in infants has come from studies measuring DEM responses to moving plaid patterns. The notion is that if infants possess global motion mechanisms, then they should generate eye movements in the direction of the integrated plaid pattern, which is different from the direction of either of the underlying component gratings. Results using this method have shown that infants as young as 2 months possess mechanisms that signal the global pattern direction (Dobkins, Fine, Hsueh, & Vitten, 2004; Manny & Fern, 1990). Further evidence for the existence of global motion mechanisms in infants has come from studies showing that infants as young as 2 months of age make directionally appropriate eye movements in response to stochastic motion displays (Dobkins & Sampath, 2008; Mason, Braddick, & Wattam-Bell, 2003). In FPL studies, it has been shown that infants prefer to look at displays in which global motion dots move in different directions over displays with just one direction, showing they can discriminate global motion direction (Banton et al., 2001; Bertenthal & Bradbury, 1992; Dannemiller & Freedland, 1991; Mason et al., 2003; Wattam-Bell, 1996b).

Despite the early emergence of global motion processing in development, it has been suggested that it takes a long time to develop to an adult-like state, based on reports that directional discrimination of stochastic motion displays may not be adult-like until early to late childhood (Bucher et al., 2006; Ellemberg et al., 2004; Ellemberg et al., 2003; Giaschi & Regan, 1997; Gunn et al., 2002; Hadad, Maurer, & Lewis, 2011; Hollants-Gilhuijs, Ruijter, & Spekreijse, 1998; MacKay et al., 2005; Narasimhan & Giaschi, 2012; Parrish, Giaschi, Boden, & Dougherty, 2005; Schrauf, Wist, & Ehrenstein, 1999; Taylor, Jakobson, Maurer, & Lewis, 2009). Similar evidence for protracted development of global motion processing has been reported for monkeys as well (see Kiorpes & Movshon, 2004b; Kiorpes, Price, Hall-Haro, & Movshon, 2012; Movshon, Kiorpes, Hawken, & Cavanaugh, 2005). For example, Kiorpes and colleagues (2012) examined the development of global motion and global form perception in macaque monkeys, and found that both types of sensitivities took about 2 to 3 years to reach an adult-like level, which is comparable to early adolescence for humans, given the differences in maturation rates between species. One obvious explanation for protracted development of global motion abilities, despite the early emergence, is that higher-level motion areas, like MT, may possess basic functionality early on, but take time to reach adult-like motion sensitivity. That is, even though neurophysiological recordings from neurons in area MT of monkeys as young as 1-week-old revealed adult-like directional selectivity, despite lower responsivity (Movshon, Rust, Kohn, Kiorpes, & Hawken, 2004, and see Chino et al., 1997 for a similar finding in V1). However, there may be that significant immaturities in the integration of motion signals could underlie the behavioral immaturities and extended protracted development of coherent motion sensitivity.

An alternative possibility for why global motion processing may appear protracted is slow maturation of sensitivity to the stimuli typically employed to test global motion (i.e., dots in stochastic motion displays). For example, if the dots are small, and spatial acuity is still immature, then the protracted development of global motion processing could arise at the level of the *input* to global motion detectors, as opposed to an immaturity of the global motion detectors themselves. As we have previously pointed out (Dobkins, 2005; Dobkins & Teller, 1996b), studies of the development of motion processing in infants need to control for developmental changes in the *sensitivity* of the mechanisms providing input to motion mechanisms. In our previous motion study that addressed this, we measured (light/dark) contrast thresholds for the ability to discriminate the *direction* of moving gratings, in terms of multiples of the contrast threshold needed to simply *detect* the moving gratings, and found that infant motion mechanisms look fairly adult-like at 3 months of age (Dobkins & Teller, 1996a). In addition to manipulating contrast to control detectability, contrast is also an important feature to consider in the domain of motion processing. Several studies in adults have shown that contrast (as well as stimulus size) influences motion processing abilities. This has been shown in global motion processing, using stochastic motion displays (Edwards, Badcock, & Nishida, 1996; Tadin & Lappin, 2005; Tadin, Lappin, Gilroy, & Blake, 2003) and in local motion processing, using gratings (Boulton & Hess, 1990; Nishida, Ashida, & Sato, 1997; Takeuchi, 1998; Thompson, 1982; Thompson, Brooks, & Hammett, 2006).

In the current study, we addressed the issue of controlling detectability/sensitivity by employing global motion stimuli that were first equated for detectability using a local motion stimulus, with the notion that local motion signals provide the input to global motion mechanisms. This method allowed us to equate the input to global motion mechanisms across different ages, and also across different individuals within each age group. We used the DEM procedure, previously used to reveal directional discrimination in infants and adults (Dobkins et al., 2004; Dobkins & Sampath, 2008; Mason et al., 2003). For each subject, the first "local" motion task used a stochastic motion display consisting of a field of dots uniformly moving leftward or rightward. The contrast of the dots was varied across trials to obtain a contrast threshold. This was a local motion task because all the dots moved coherently, and therefore any single (local) dot was informative about the motion direction. The second "global" motion task presented each subject with a stochastic motion display where the contrast of the dots was set to 2.5 × each individual's contrast threshold for the local task, and then the coherence (percentage of signal vs. noise dots) was varied to obtain a coherence threshold. The results of this study showed remarkably constant coherent (global) motion sensitivity between 3 and 7 months, as well as between infancy and adulthood.

Methods

Subjects

Infants

All infants were recruited by mass mailings to new parents residing in San Diego County. A total of 57 infants took part in this study. The inclusion criterion for infants was that the length of their gestational period was between 39 and 41 weeks, and that they had normal, uncomplicated births. Infants were tested within a week of their 3-, 4-, 5-, 6-, and 7-month birthdays. Four infants did not return for a second testing session, five failed to meet the minimum trials criterion ($N > 140$) due to fussiness, and three infants had data that were too noisy to fit a threshold; therefore, these 12 infants were not included in the analysis. Nine infants were included in the final analysis for each age group, for a total sample of 45 infants. The average age of subjects in each group is listed in Table 1.

Adults

Adult subjects were tested under stimulus conditions nearly identical to those employed in our infant paradigm. Twelve naive viewers participated in these experiments. Data from six adults were excluded because they were at ceiling in the contrast sensitivity condition and therefore a contrast threshold could not be obtained. The final sample included six adults, aged 20–23 years (M age = 21.71 years, SE = 5.37 months). All had normal or corrected-to-normal vision.

Stimuli

Stimuli were presented on an HP p1230 monitor (1024 × 768 pixels, 75 Hz) powered by a Dell Precision T5500 Workstation computer and viewed at a distance of 42 cm. The stimulus conditions used in these experiments are shown in Figure 1. Stimuli consisted of a stochastic motion display (after Newsome & Paré, 1988; Williams & Sekuler, 1984), which subtended 63.20° × 55.40°. In total, 600 dots (1° × 1°; dot density = 1 dot per degree^2) were presented on a gray background (5.51 cd/m^2). A portion of these dots were "signal dots" that were displaced horizontally (to the left or right) by 0.42° every vertical refresh (every 13.33 ms), which created coherent leftward or rightward motion at 31.5°/s. Signal dots had limited lifetimes; each dot lasted 267 ms (20 vertical refreshes) before disappearing and reappearing in a new location.[1] Five percent of the coherent dots on any given frame ended their lifetime and their successor dots appeared at a

Age group (months)	*N*	Mean age (*SEM*)
3	9	3.10 (0.04)
4	9	4.10 (0.10)
5	9	4.97 (0.06)
6	9	6.06 (0.10)
7	9	6.90 (0.08)

Table 1. Age distribution of infant subjects.

random position on the screen. Consequently the maximum effective coherence of the display was 95%. Coherence values reported here took into account this reduction of coherence due to limited dot lifetime. The rest of the dots were "noise" dots that were randomly relocated every 13.33 ms, and did not have a uniform motion percept. The combination of low dot density and small spatial displacement of the signal dots should result in a low probability of spurious motion signals occurring.

In the *Contrast Sensitivity* condition, the coherence level was fixed at 95%, and the luminance of the dots was varied to obtain a contrast threshold (infants: 5.62–31.22 cd/m^2, adults: 5.52–8.27 cd/m^2, which translates to Michelson contrasts of 1.00%–70.00% for infants and 0.10%–20.00% for adults). In the *Coherence Sensitivity* condition, the contrast of the dots was set at 2.5 × the subject's contrast threshold (determined from the preceding Contrast Sensitivity condition), and the proportion of signal dots was varied to obtain a coherence threshold (infants: 9.50%–95.00%, adults: 9.00%–90.00%). Using method of constant stimuli, seven levels of contrast or coherence values, in equal log steps, were presented to subjects, randomly across trials. The use of stimuli that were 2.5 × contrast threshold ensured that the stimuli in the Coherence Sensitivity condition were equally detectable across the different subjects and age groups.

Procedure

Infant testing procedure

In order to measure direction discrimination, we used a "directional eye movement" (DEM) technique, which relies on the fact that both adults and infants

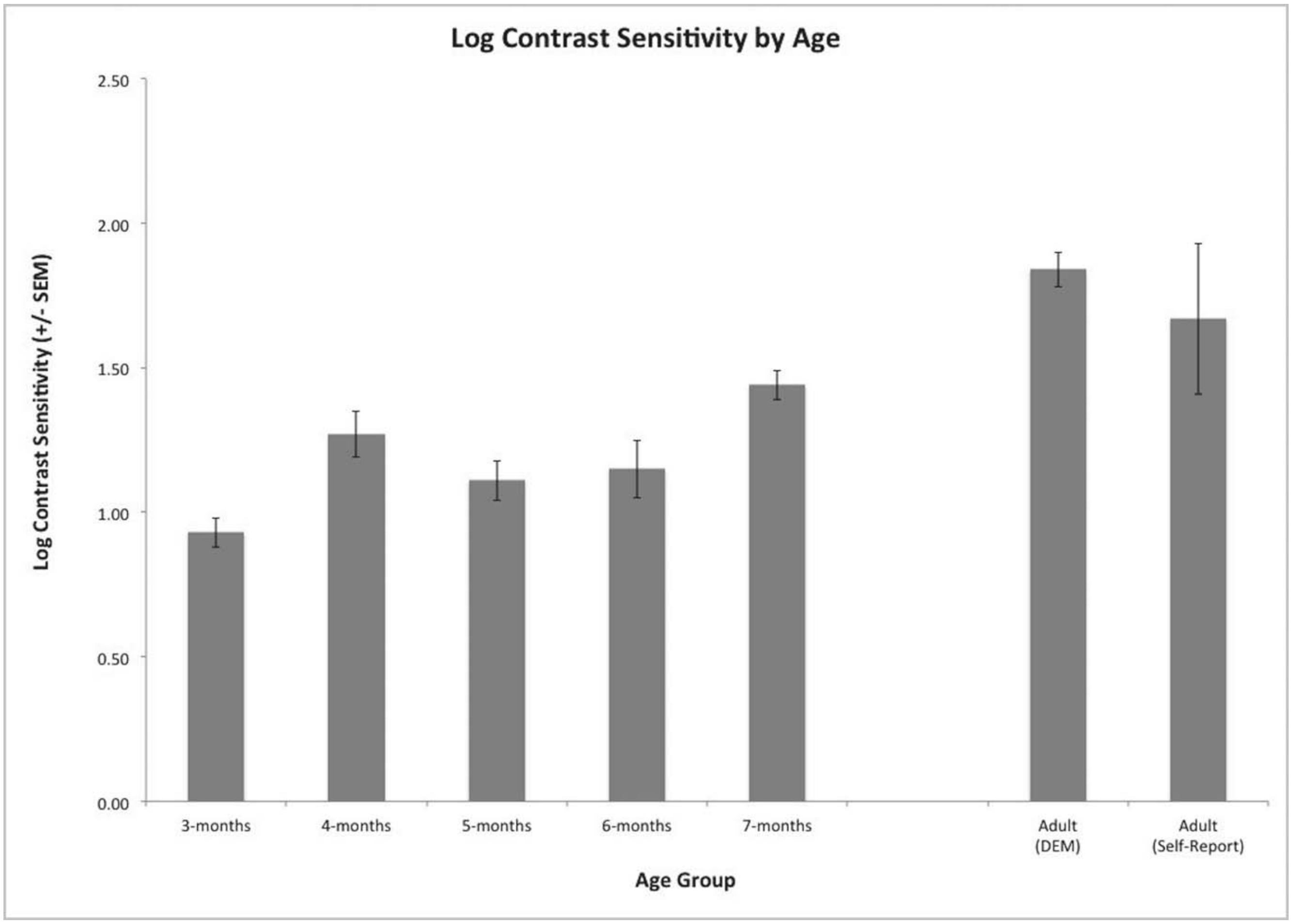

Figure 1. Mean log contrast sensitivity for each age group using DEM and for adults, using DEM and self-report. Error bars denote *SEM*.

Age group	Log contrast sensitivity	Linear % contrast threshold	Log coherence sensitivity	Linear % coherence threshold
3	0.93 (0.15)	11.7%	0.54 (0.21)	28.8%
4	1.27 (0.24)	5.4%	0.55 (0.18)	28.2%
5	1.11 (0.21)	7.8%	0.56 (0.27)	27.5%
6	1.15 (0.30)	7.1%	0.50 (0.30)	31.6%
7	1.44 (0.15)	3.6%	0.69 (0.24)	20.4%
Adult - DEM	1.84 (0.15)	1.4%	0.38 (0.34)	41.7%
Adult - self-report	1.67 (0.64)	2.1%	0.33 (0.37)	46.8%

Table 2. Means and standard deviations for log contrast and coherence sensitivity at each age group tested. The percent contrast and coherence thresholds are provided as well, which were computed as the antilog of 1/sensitivity.

make directionally appropriate eye movements in response to moving stimuli (e.g., Dobkins & Teller, 1996b; Hainline, Lemerise, Abramov, & Turkel, 1984; Kremenitzer et al., 1979). These eye movements can include optokinetic nystagmus (OKN), smooth pursuit, and/or saccades when using a medium-sized moving display as used in the current study (63.2° × 55.4°). An adult experimenter held the infant 42 cm away from the front of the stimulus monitor in the view of a video camera aimed at the infant's face. On each trial, the stochastic motion display was presented to the infant, and the experimenter viewed the video of the infant's eye movements to judge the left versus right direction of motion of the stimulus. Stimuli remained present on the monitor until the experimenter made the left/right judgment, which was typically less than 2 s. The parent (who could not see the stimulus) entered the experimenter's answer into the computer by pressing keys on the keyboard. Computer beeps provided feedback as to whether the experimenter was correct. Data from each infant were obtained over the course of 2 days within a 1-week period, and each daily session lasted approximately 45 min.

First, the subject was tested on the Contrast Sensitivity condition. For each subject, a Weibull function and maximum likelihood analysis (Watson, 1979; Weibull, 1951) were used to determine contrast threshold, defined as the contrast yielding 75% correct directional discrimination performance. Next, the subject was tested on the Coherence Sensitivity condition, with the contrast of dots set to 2.5 × each subject's contrast threshold. Across subjects, the mean number of trials for the Contrast and Coherence Sensitivity conditions were 74 (±19) and 67 (±18) for infants. Adults were tested on 200 trials for each condition. These data were fitted with Weibull function to obtain coherence thresholds, defined as the contrast or coherence yielding 75% correct directional discrimination performance. Contrast Sensitivity and Coherence Sensitivity values were computed as the inverse of threshold × 100, and then logged (base of 10), since log, but not linear, sensitivity data conform to normal distributions (Graham, 1989).

Adult testing procedure

Adults were tested under two different procedures, first using a DEM technique and then a self-report technique. The DEM procedure was similar to that used with infants with the exception that the stimuli were limited duration (400 ms). As with infants, a contrast threshold was first obtained in the Contrast Sensitivity condition, and then used to set the contrast at 2.5× in the Coherence Sensitivity condition. After the DEM measure, each adult participated a second time using a self-report measure, where they pressed keys to indicate the perceived direction (leftward or rightward) of the motion stimulus. Like the DEM, a contrast threshold was first obtained in the Contrast Sensitivity condition, and then used to set the contrast at 2.5× in the Coherence Sensitivity condition. For the self-report procedure, we had to use a shorter duration (100 ms) than in the DEM condition. This is because in pilot studies we found that there was no single duration that could be used for *both* DEM and self-report; i.e., longer durations yielded good psychometric functions for DEM, yet ceiling performance in the self-report, while shorter durations yielded good psychometric functions for the self-report, yet floor performance in DEM. We believe the difference in duration used for DEM versus self-report is not a major concern because comparisons we make between those two conditions are only for the Coherence Sensitivity measure, where, by definition, the stimuli are equated with respect to performance in the Contrast Sensitivity measure. Obviously, contrast thresholds will differ for different durations, as well as for DEM versus self-report, and therefore contrast thresholds for the two different testing conditions are not compared in the current study.

Data analysis

For the purpose of plotting data, group mean log contrast and coherence sensitivities were obtained by averaging log sensitivities across subjects within each age group. One-way analyses of variance (ANOVAs) with age as a between-subjects factor was conducted on log sensitivity values. These ANOVAs were conducted separately for contrast and coherence sensitivity. For the coherence sensitivity data, ANOVAs were conducted with adult data included and excluded, to determine if any effects were driven by an overall difference between infant and adult performance or by a developmental increase in sensitivity beginning in early infancy. Post-hoc tests were conducted between the five infant age groups to determine what drove the differences in the ANOVA. Because there were multiple age comparisons, we report only data that were significant with a Bonferroni-corrected alpha adjusted to $p = 0.005$ (10 comparisons). Finally, for adult data, paired *t* tests were employed to determine if there were differences between coherence sensitivity obtained with DEM versus self-report.

Results

Contrast sensitivity

Group mean contrast sensitivity for discriminating direction of motion as a function of age group is plotted in Figure 1. As expected, contrast sensitivity increases with age in infants. This is supported by the results of a one-factor ANOVA on infants' contrast sensitivity showing a significant main effect of age, $F(4, 40) = 6.09$, $p < 0.001$; $\eta_p{}^2 = 0.40$. Post-hoc comparisons revealed a significant difference between 3- versus 4-month-olds ($p = 0.003$), 3- versus 7-month-olds ($p < 0.00005$), and 5- versus 7-month-olds ($p = 0.004$). When all infants were combined, adults were significantly more sensitive than infants, $t(49) = 8.82$; $p < 0.0005$. This comparison is not quite fair, however, since infants were tested with unlimited duration and adults were tested with limited durations (see Methods). Presumably, had adults been likewise tested with unlimited duration, their contrast sensitivity would be even greater. Similarly, a comparison between adult contrast sensitivity obtained for DEM versus self-report is not meaningful since different durations were required for the two conditions (see Methods). Nonetheless, there was no difference between the two, $t(5) = 0.67$, $p = 0.53$.

Coherence sensitivity

Group mean log coherence sensitivity for discriminating direction of motion as a function of age group is plotted in Figure 2. Like the data in Figure 1, infant data were obtained with DEM, while adult data were obtained for both DEM and self-report. For adults, a comparison of adult coherence sensitivity between the two procedures (DEM vs. self-report) is meaningful, since the procedures were first equated in the Contrast Sensitivity condition (as discussed above in Methods). The results show that coherence sensitivity did not significantly differ between DEM versus self-report, $t(5) = 0.28$, $p = 0.79$.

With regard to the effects of age on coherence sensitivity, Figure 2 reveals markedly constant coherence sensitivity across age. With adult data excluded, the results of a one-factor ANOVA showed no significant effect of infant age, $F(4, 40) = 0.84$, $p = 0.51$. With adult data included, the results of a one-factor ANOVA also showed no significant effect of age, $F(5, 45) = 1.50$, $p = 0.21$. In addition, when all infants were combined, there was no significant difference between infants and adults, $t(49) = 1.27$, $p = 0.21$. In sum, the results show rather constant coherence sensitivity across ages, between 3 to 7 months, and between infancy and adulthood.

Discussion

The current study is the first, to our knowledge, to study development of global motion sensitivity in human infants and adults, controlling for possible developmental changes and individual differences in sensitivity of the local motion mechanisms that provide input to global motion detectors. Stated differently, the global motion stimulus employed in our study was equated in lower-level contrast detectability across subjects. Under these conditions, we found remarkably stable global motion sensitivity between 3 and 7 months of age, as well as between infancy and adulthood, while contrast sensitivity improved with age, as expected. The flat developmental trajectory for global motion is in striking contrast to what is known about the development of temporal resolution (Apkarian, 1993), contrast sensitivity (Atkinson, Braddick, & Braddick, 1974), spatial acuity (Banks & Salapatek, 1978), vernier acuity (Manny & Klein, 1985; Shimojo, Birch, Gwiazda, & Held, 1984) and binocularity (Shimojo, Bauer, O'Connell, & Held, 1986), which all show steep improvement between 1 and 6 months of age.

Directional eye movements

Before proceeding with the Discussion, we address the use of our eye movement technique (DEM), which relies on subjects making directionally appropriate eye movements in response to moving stimuli. The first issue regarding the use of this technique is whether eye movements can be considered reliable indicators of

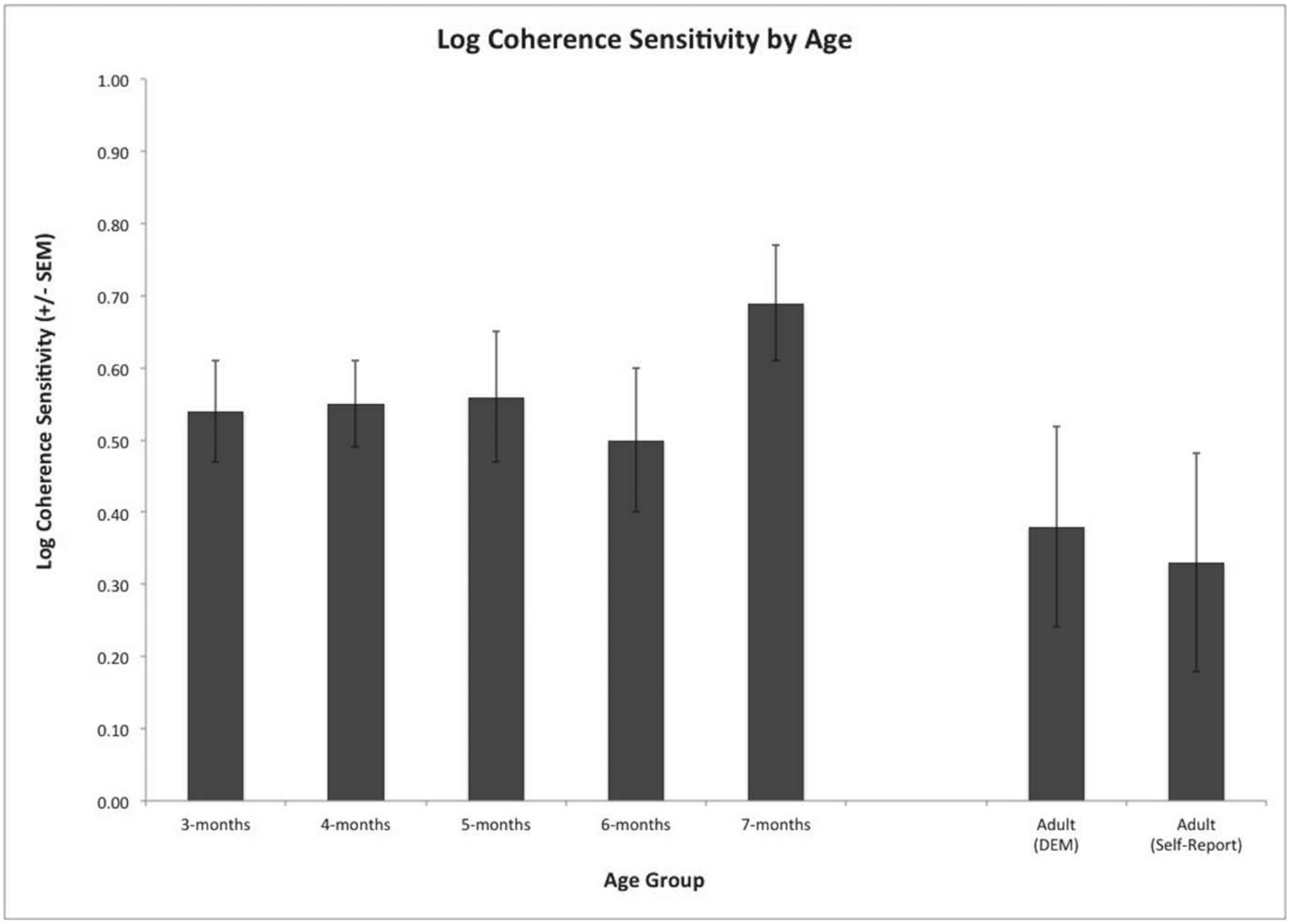

Figure 2. Mean log coherence sensitivity for each age group using DEM and for adults, using DEM and self-report. Error bars denote *SEM*.

motion perception. In adults, it has been shown that the direction of eye movements and perceived direction are highly correlated with each other (e.g., Beutter & Stone, 1997; Manny & Fern, 1990; Stone & Krauzlis, 2003; Yo & Demer, 1992). Because it is essentially impossible to ascertain what an infant perceives, we must, to a certain extent, take it on faith that the same relationship between eye movements and perception holds in infants. The second issue is whether DEM is mediated by subcortical motion mechanisms or by cortical motion mechanisms that exert control over subcortical mechanisms. It has been suggested that one particular type of eye movement, optokinetic nystagmus (OKN), is mediated predominately by subcortical motion mechanisms in very young infants. (Although note that not all eye movements in our study were OKN-like. Our impression was that in both infants and adults, approximately half of the eye movements we observed were OKN-like in nature, with the rest resembling pursuit eye movements, thought to be mediated be cortical mechanisms [Hainline, 1993; Hoffman, 1981].) Although this is believed to be true at younger ages, after 3 months of age (the youngest age in the current study), OKN is thought to be controlled primarily by cortical mechanisms (Atkinson & Braddick, 1981), and with increasing age, there is greater cortical control over DEM (Atkinson & Braddick, 1981; Braddick, 1996; Hoffman, 1981; Mason et al., 2003; Morrone et al., 1999). For this reason, we believe that the data we obtained are mediated predominantly by cortical mechanisms (see similar arguments in Dobkins et al., 2004; Dobkins, Lewis, & Fine, 2006; Dobkins & Sampath, 2008).

Developmental trajectories for global motion processing in infancy

The results of our study add to the growing body of literature showing early emergence of global motion mechanisms; by 1.5 to 2 months of age, infants can integrate and discriminate direction of motion in stochastic motion displays (Atkinson et al., 1992; Banton & Bertenthal, 1996; Banton et al., 2001; Birch et al., 2000; Bosworth & Birch, 2005, 2007; Hamer & Norcia, 1994; Wattam-Bell, 1991), integrate the component grating motions that make up plaid patterns (Dobkins et al., 2004; Dobkins et al., 2006), and integrate the 1D and 2D signals in the barber pole illusion, which is a type of global motion processing (Dobkins et al., 2006). However, the nature of *developmental trajectories* for global motion mechanisms has been a matter of debate. With respect to the period during *infancy*, the current study observed a flat trajectory. This finding is, in fact, consistent with results from other studies of global motion processing in infants (see Hamer & Norcia, 1994, and Mikami & Fujita, 1992, for similar conclusions regarding development of local motion processing). For example, using DEM to obtain coherent motion sensitivity, it has been reported that coherence sensitivity is constant across the ages tested in this study (1.5–4.5 months: Banton & Berthenthal, 1996; 1–7 months: Mason et al., 2003). Using DEM to obtain the relative weighting of the integration of 1D and 2D signals in the "barber-pole" illusion, Dobkins et al. (2006) reported a constant relative weighting of 1D versus 2D motion signals across the ages tested, 2 and 5 months.

One noted exception to a flat developmental trajectory for global motion processing is an FPL condition in the Mason et al. (2003) study (which they compared to their DEM condition, cited above). In this FPL condition, they measured coherent motion sensitivity in a display where one side had a single direction of motion, i.e., "same motion" (all leftward or all rightward), and the other side had "opposite motion" (an upper and bottom panel moved rightward while the middle panel moved leftward). The use of this stimulus in conjunction with FPL has two assumptions. First, if an infant can discern leftward from rightward, they will notice the difference between the two sides of the display. Second, the infant will prefer to look at the "opposite motion" side because it is presumably more interesting. The results of the Mason et al. (2003) study revealed lower overall motion coherence sensitivity for the FPL method than for the DEM method and, unlike DEM-based sensitivity, FPL-based sensitivity increased with age. These differences between the DEM and FPL results led Mason et al. (2003) to conclude there exist different mechanisms for FPL-based (more cortical) versus DEM-based (which they argue is more subcortical) motion sensitivity. While we do not refute this, there are two important caveats to be made. First, it is not surprising that overall sensitivity appears greater for the DEM than the FPL method. This is because whereas the DEM method is somewhat involuntary (i.e., one's eyes are "dragged along" with the stimulus), the FPL method not only requires voluntary looking, but it requires that infants find the "opposite motion" side more interesting than the "same motion" side. In our own laboratory (unpublished observations), we have found this latter assumption to not always be the case, i.e., infants seem to find both uniform and segmented moving patterns interesting and look back and forth between the two, making it very difficult to determine which side they prefer. Second, closer inspection of the Mason et al. (2003) data seem to show that the age-related change in FPL-based motion sensitivity occurs only within the first two months. Like their DEM data (and the DEM data of the current study, and Banton & Bertenthal, 1996), the developmental trajectory for their FPL-based motion sensitivity appears flat between 3 and 7 months. In other words, the most marked difference between the DEM and FPL data of Mason et al. (2003) is between 1 and 2 months, where there is age-related improvement in FPL- but not DEM-based motion sensitivity. This very well might be explained by different mechanisms underlying FPL (more cortical) and DEM (more subcortical) at these very young ages, as the authors proposed. However, we return to our primary argument that motivates this study, which is that the age-related improvement in FPL-based motion sensitivity could be secondary to age-related changes in the sensitivity of mechanisms that provide input to motion mechanisms underlying FPL performance (and presumably the sensitivity of mechanisms that provide input to motion mechanisms underlying DEM performance, by comparison, is relatively stable across infant ages; see below). It is perhaps important to point out that, even *without* controlling for detectability—the above-mentioned previous studies observed a flat coherent motion sensitivity trajectory, at least past 3 months of age. This finding suggests that—over the time period measured in infancy—there are negligible changes in the sensitivity of the mechanisms providing input to global motion detectors.

However, just because a given study finds a flat trajectory when not controlling for detectability, one should not be compelled to argue that it is not necessary to control for detectability. Each motion experiment is different, and if one's results indicate an age-related improvement in motion abilities, then one ought to make sure this effect is not secondary to age-related differences in sensitivity (see Dobkins, 2005). We realize that past studies have attempted to circumvent this problem by using stimuli presented at very high contrast, with the assumption that they are detectable at all ages tested. However, even maximum contrast stimuli are likely to vary in *perceived* contrast with age, especially between infancy and adulthood. Given that motion processing abilities are affected by perceived contrast (Edwards et al., 1996; Tadin & Lappin, 2005; Tadin et al., 2003, see Introduction), not controlling this aspect of the stimulus is likely to influence results. Accordingly, the above-mentioned studies by Banton and Bertenthal (1996) and Mason et al. (2003) did find significantly greater coherent motion sensitivity in adults than infants, and this result is likely due to the stimuli being of higher perceived contrast to adults (as well as adults being more cooperative). In contrast, in the current study we found that when infants and adults are tested with equally detectable stimuli (in terms of contrast), infants did not have worse coherent motion sensitivity compared to adults. Likewise, in our past barber-pole study (Dobkins et al., 2006), we found that the relative weighting of 1D and 2D motion integration was the same for infants and adults, only when infants and adults were tested with equally detectable stimuli. In sum, the results from several studies suggest that global motion mechanisms develop very early, may be stable in the first year of life, and have the added possibility of being adult-like as early as three months. Still, as a caveat, it is worth noting that the current study employed only one combination of speed, dot displacement size, and density, which are parameters that can affect global motion processing (e.g., Hadad et al., 2011; Narasimhan & Giaschi, 2012; Parrish et al., 2005), and so it is possible that the fast development of global motion processing we observed exists under some, but not all, conditions. Along these lines, variation across studies in these stimulus parameters could account for some of the discrepancy in the rate of maturation of global motion seen across studies.

Protracted development of global motion processing during childhood?

Despite our proposal that global motion mechanisms may be adult-like early in infancy, there exists a contrary literature suggesting that there exists protracted development of motion mechanisms into late childhood. It has been reported that motion coherence sensitivity is not adult-like until sometime between 7 and 12 years of age (Armstrong, Maurer, & Lewis, 2009; Bucher et al., 2006; Ellemberg et al., 2003; Giaschi & Regan, 1997; Gunn et al., 2002; Hadad et al., 2011; Parrish et al., 2005). Yet, as we continue to argue, one possibility not considered in many of these studies is age-related improvement in motion abilities may partly reflect (uncontrolled) age-related changes in contrast sensitivity (e.g., Hou, Gilmore, Pettet, & Norcia, 2009; Kanazawa, Shirai, Ohtsuka, & Yamaguchi, 2006; MacKay et al., 2005; Weinstein et al., 2012). There are mixed results about when contrast sensitivity is adult-like, with some studies reporting full maturity by 7 years (e.g., Ellemberg, Lewis, Liu, & Maurer, 1999) and others not until much later in life (Abramov et al., 1984; Beazley, Illingworth, Jahn, & Greer, 1980; Bradley & Freeman, 1982; Crognale, 2002; Knoblauch, Vital-Durand, & Barbur, 2001). In addition, spatial acuity may have a protracted development (Atkinson, 1984; Ellemberg et al., 1999; Hainline & Abramov, 1997), and therefore, the dots used in typical stochastic motion displays may be relatively too small for younger children to resolve perfectly. However, arguing against this possibility are studies that have reported that coherent motion sensitivity does not correlate with measures of contrast sensitivity or spatial acuity (for example, Ellemberg et al., 2002; Giaschi, Regan, Kraft, & Hong, 1992; Hess, Demanins, & Bex, 1997; Ho et al., 2005). There is another reason we believe coherent motion sensitivity may not look adult-like until later in childhood, which is based on our own observations of having worked with stochastic motion displays for many years (Dobkins & Bosworth, 2001; Dobkins & Sampath, 2008; Thiele, Rezec, & Dobkins, 2002). Occasionally, subjects experience motion induction, i.e., the signal dots seem to make the noise dots move in the opposite direction. We suspect that this happens in children too, with the difference being that children do not have the vocabulary (or the desire) to explain that this phenomenon is occurring (and therefore, it is uncorrected). As such, there are probably many more trials in children, than in adults, where subjects get confused in this manner. In turn, this will lead to lower performance (i.e., lower estimates of coherent motion sensitivity) in children than in adults. Of course, a future study that systematically tests this possibility is required. At the very least, it would be interesting to obtain self-report-based and DEM-based sensitivity in children, and compare the results to those of adults. We hypothesize that children and adults would be indistinguishable on the DEM measure (because it is largely involuntary), but children would underperform adults on the self-reports for the reasons described above.

Keywords: local motion, global motion, infants, adults, contrast, coherence, stochastic motion

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Footnote

[1] This dot lifetime (267 ms) was chosen based on our pilot studies with infants. This is longer than is typically used in studies employing stochastic motion displays with adults but is still well within the limited range used with infants and children (e.g., Ellemberg et al., 2004; Hadad, Maurer, & Lewis, 2011; MacKay et al., 2005; Taylor, Jakobson, Maurer, & Lewis, 2009). Since the dot lifetime was still limited, this task is considered a global motion task.

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