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EXPLORING CHILDREN'S OPTIC FLOW SENSITIVITY

A Thesis in

Psychology

by

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 $\ensuremath{\mathbb{C}}$ 2012 Amanda L. Thomas

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ABSTRACT

Motion cues are important for successful navigation in an environment. The structured global motion pattern, optic flow, provides a person with speed and direction information about her self-motion. Prior research has shown that, radial (expansion/contraction) optic flow patterns elicit robust evoked potential responses in adults, while responses to rotation and translation (left/right) patterns are weaker. Comparatively, infants show the strongest evoked responses to lateral translation. Previous studies also suggest that adult-like spatial and temporal tuning to global motion develops over a prolonged time period. However, the literature is still lacking a component that connects adult and infant optic flow research and provides a clear trajectory of optic flow sensitivity over time. The current study attempts to provide this missing information. For this study, steady-state visual evoked potential (SSVEP) responses were recorded from children of 4 to 8-years to coherence modulations of three optic flow pattern types (lateral translation, rotation, and radial expansion/contraction) at 3 different speeds (2, 4, and 8 deg/s), using an electrode net of 128 channels. Children viewed moving dot displays (7 amin dots, 79.4 cd/m^2 , density = 10%) that modulated in time from incoherent to 100% coherent global motion at 1.2 Hz (F1). All displays had the same dot update rate (24 Hz, F2). Overall, responses to coherence modulation were largest for the radial patterns and were tuned for fast speeds. The oldest children were the most adult-like, with weak responses to translation and rotation, but the strongest responses to radial motion. Robust responses to translation were still observed in the youngest children. The results suggest that adult-like sensitivity to optic flow patterns emerges in middle childhood and that there are multiple trajectories associated with the development of optic flow processing.

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Chapter 1: The visual system and optic flow

One of the visual system's major tasks is guiding an individual's movement through the environment (Britten, 2008). Optic flow, the structured pattern of global motion, provides individuals with information about their speed and direction of self-motion (Britten, 2008; Gibson, 1950), as well as information about the shape and trajectory of moving objects. Computational analyses suggest that optic flow patterns experienced by moving observers consist of combinations of elementary translation, expansion, rotation (see Figure 1), and deformation components (Koenderink, 1986). Therefore, the visual system may decompose optic flow into its elementary components in order to accurately estimate self- and object motion. How this occurs in adults is not yet fully understood, but developmental data from both nonhuman primates and human infants suggests that sensitivity to motion develops at a slower rate than other visual aspects of visual function, such as contrast sensitivity or visual acuity (Britten, 2008; Gilmore, Hou, Pettet, & Norcia, 2007; Hou, Gilmore, Pettet, & Norcia, 2009; Kiorpes & Movshon, 2004). There is also evidence that different flow components evoke distinctive cortical responses in adults, but not consistently in infants, suggesting that neural sensitivity to basic optic flow components develops at different rates (Gilmore et al., 2007).

The visual system undergoes considerable development through infancy and childhood (Gordon & McCulloch, 1999). While much is known about motion processing in the infant brain, much less is known about changes in this type of processing among preschool and school-aged children. Previous research exploring the visual abilities of children in this age range has produced contrasting results concerning when spatial and temporal vision reaches adult maturity (Ellemberg, Lewis, Liu, & Maurer, 1999). For example, Arundale (1978) found that children 8-15 years of age exhibit spatial contrast sensitivity that is immature relative to adults. In contrast,

other researchers report that children as young as 6 years old demonstrate spatial contrast sensitivity comparable to that of adults or that a time of maturity could not be determined (Mahtyjarvi, Autere, Silvennoinen & Myohanen, 1989; Scharre, Cotter, Stein-Block & Kelly, 1990; Gwiazda, Bauer, Thorn, & Held, 1997). Multiple studies have indicated that both the human and non-human primate visual systems mature gradually (Kiorpes et al., 2004; Britten, 2008; Giaschi & Regan, 1997). Neither spatial nor temporal sensitivity is adult-like through early to middle childhood (Swanson & Birch, 1990; Hartmann & Banks, 1992; Ellemberg et al., 1999). The current study will determine the developmental trajectory of sensitivity to different patterns of optic flow in preschool and school-aged children. In particular, the study will explore sensitivity to flow patterns that differ in global speed and motion coherence so that data from children may be compared with that collected from adults and infants under similar conditions.

Brain development and motion processing

Understanding the detailed mechanisms that underlie global motion perception is of particular importance in visual neuroscience. Research has indicated that the middle temporal extrastriate cortex is a brain region highly involved in processing this type of motion (Maunsell & Newsome, 1987). Lesions in area MT lead to the inability to perceive global motion (Barton, Sharpe, & Raymond, 1995). Loss of perception stems from an inability to integrate local motion cues into global patterns. Cells in MT receive extensive input from area V1 where there are cells that indicate motion direction in local areas of the visual field (Newsome & Pare, 1988; Vaina et al. 1998). MT cells have large receptive fields and varying preferences for speed and direction of motion (Maunsell & Van Essen 1983, 1987; Albright, 1984). Retinal or cortical immaturities may, restrict what information reaches higher order visual areas (Ellemberg et al., 1999). Additionally, the integration of complex motion can also be disturbed by the interruption of

magnocellular pathway processing (Chapman, Hoag & Giaschi, 2004). Therefore exploring the development of global motion sensitivity, which depends on processing in higher order areas, may allow for greater understanding about where and when functional changes are occurring in the developing visual brain.

Ellemberg and colleagues (1999) investigated the development of spatial and temporal vision in 4, 5, 6, and 7-year-olds and adults. In this study children monocularly viewed vertical sinusoidal gratings on a screen at a distance of 57 cm. For the spatial condition, gratings were displayed at .33 to 20 cycles per degree and either increased in contrast from below threshold to threshold or descended from suprathreshold. Children were asked to say "gone" when the stimulus disappeared when descending from threshold to subthreshold or they were instructed to answer "there" when the gratings appeared when ascending from below threshold to threshold. This was done for 3 ascending and 3 descending thresholds. Temporal contrast sensitivity was measured similarly, with a spatially unpatterned light source stimulus that varied in luminance (Ellemberg et al., 1999). In these trials, children said "gone" when the light no longer flickered or "there" when the flicker returned due to increases or decreases in temporal frequency. Although the child subjects were very close in age there were measurable differences in both spatial and temporal contrast sensitivity. For spatial contrast sensitivity, children aged 4 and 5 performed alike displaying low sensitivity at all eight spatial frequencies. The 5-year-olds' contrast sensitivity was much lower than that of the 6-year-olds. The 6-year-olds were also significantly different from the 7-year-olds with much lower contrast sensitivity. Only the 7year-olds matched the contrast sensitivity of adults. The younger age groups also demonstrated immature temporal contrast sensitivity, but only at low temporal frequencies. The results suggest that temporal and spatial contrast sensitivity develop at different rates with the latter

maturing at a faster rate (Ellemberg et al., 1999). These researchers assert that patterns of growth in the retina best account for the differences in spatial and temporal vision during childhood although others (Banks & Bennett, 1988; Braddick & Atkinson, 2011) have suggested that both retinal and cortical immaturities contribute to the prolonged pattern of postnatal visual development in humans. Nevertheless, studies such as this one demonstrate the importance of sampling within small age ranges in early childhood to accurately capture subtleties in the development of visual function.

Four to seven-year-olds also differ from adults in terms of motion processing. When comparing adult and child sensitivity to first-order (luminance-modulated) and second-order (contrast-modulated) motion, Ellemberg and colleagues found greater differences in thresholds between adults and children (5-year-olds) for second-order order motion than for first-order order motion (Ellemberg, Lewis, Meghji, Maurer, Guillemot, & Lepore, 2003). The participants viewed a horizontal grayscale sine-wave pattern that varied in luminance, contrast, and speed (1.5 deg/s and 6 deg/s) and were asked to discriminate direction of motion (up or down). Overall the children were less sensitive to the stimuli than the adults. Child thresholds for the first-order stimuli were similar to the second-order at 1.5 deg/s. However at the faster speed, the second order threshold was 8 times greater. These results indicate that sensitivity to each of these motion types develops at different rates, with second-order sensitivity developing at a slower rate than first-order. Additionally, these findings suggest that these children show more adult-like behavioral sensitivity to low speeds as compared to high speeds. Their results also provide support for the idea that processing of second-order motion involves neuronal mechanisms that are distinct from those in first-order motion, which has also been found in a neuroimaging study with adults (Vaina, Makris, Kennedy, & Cowey, 1998). If these types of motion demonstrate

distinct underlying mechanisms, global motion patterns with varying properties could also have discrete mechanisms.

Optic flow sensitivity in infant, adult, and clinical populations

In a similar vein, Gilmore and colleagues (2007) uncovered developmental differences in the visual brain's response to various patterns of optic flow. In this study, both infant and adult participants viewed direction-reversing translational, rotational, and radial motion patterns at 5.5 deg/s while steady-state visual evoked potentials (SSVEP) were recorded from several electrodes along the occipital area of the scalp (PO7, O1, Oz, O2, PO8). For adults, responses to the flow reversals showed different peaks for each display type (Gilmore et al., 2007). Adults showed the largest amplitude responses to radial motion, displaying the largest responses for transitions from expansion to contraction relative to left /right and clockwise/counter-clockwise transitions. The midline channels (O1, Oz, and O2) exhibited the most robust responses to radial motion relative to the other patterns. The 4-6-month-old infants showed highly similar response waveforms for all three patterns. However they showed larger coherent responses to translational motion, with the largest amplitude responses to the coherent translation pattern. In contrast to the adults, the infants lacked systematic evoked responses across specific channels, particularly those over later areas of visual cortex. Gilmore and colleagues' (2007) findings suggest that motion processing is relatively immature in early infancy and continues to develop for some time postnatally.

In a related research paradigm in which motion coherence was modulated, the authors also found distinct evoked responses for infants as compared to adults (Hou et al., 2009). For this study, 4-6-month-old infants and adults viewed random-dot displays that changed from a coherent clockwise rotational pattern to incoherent motion. Visual evoked potentials (VEPs) were recorded from several electrodes on the occipital area. Infants and adults showed similar evoked potential responses to local motion, but different responses to temporal (on/off) modulations of global motion coherence. Global motion response tuning curves in adults peaked at small displacements and low speeds, while infant response curves peaked at higher displacements and faster speeds. Similar results have been shown in older children with visual impairments (Weinstein et al., 2011). Using SSVEP, these researchers explored global and local motion processing of children with cerebral visual impairment (CVI) using a subset of the display conditions employed by Hou and colleagues (2009). Results showed that children with CVI show relatively normal local motion processing -- robust responses to faster speeds and large displacements. However, global motion processing is impaired for these children, particularly at slow speeds. In a related behavioral study with infant macaques, researchers explored the development of sensitivity to direction of motion and the relation between motion and contrast sensitivity across time (Kiorpes et al., 2004). For the two-alternative forced-choice task, the macaques viewed random-dot kinematograms of left/right translation patterns. The experimenters judged the direction of dot motion via the optokinetic nystagmus (OKN) of the macaques. Results showed that the youngest infants discriminated motion for large dot displacements and high speeds. Motion sensitivity increased slowly over time, until the macaques were about 3-years-old, with dramatic improvements in sensitivity to motion at the slowest speeds. Taken together, these results imply that the infant primate brain responds most strongly to fast, linear flows relative to slow rotational or radial patterns. This raises the question of when and how adult-like sensitivity emerges.

A recent SSVEP study with adults (Fesi , 2012) found that brain responses to coherent modulations of global motion patterns varied by pattern type, speed, and electrode location. Adults showed robust activation to radial motion and weak responses to rotation and translation patterns. They also showed the strongest responses to the fastest speeds, which were 8 deg/s and 16 deg/s. For the radial patterns, lateral channels were the most strongly activated at the low speeds, 2 deg/s and 4 deg/s, while medial channels were the most robust at fast speeds. These results, like other findings, indicate that adults' and infants' cortical responses to global motion are distinct, thus supporting the notion of a developmental trajectory to this type of motion processing. Taken together, these studies suggest that mechanisms underlying motion processing develop over a long period of time after birth both in human and non-human primates. However, there are gaps in the existing literature about the development of the motion system. To date, no study has taken a developmental approach to the investigation of cortical responses to optic flow by systematically varying coherence and pattern type, at different speeds.

The current study extends the work of Kiorpes et al. (2004) Gilmore et al. (2007) and Hou et al. (2009). It focuses on measuring cortical responses to modulations in coherence of global motion displays, particularly left-right translation, radial expansion-contraction, and rotation across a range of speeds that ought to capture developmental trends. The design is based on the work of Fesi (2012), but with a younger population (4-8-year-olds). The current study asks the following questions: Do children's brain responses look more like infants -- favoring fast speeds and linear patterns -- or adults? Does adult-like sensitivity to optic flow patterns at different speeds emerge in middle childhood? Will children show distinct tuning for speed of optic flow patterns? If children's cortical responses are most similar to that of infants, it would suggest that maturation of global motion processing is occurring at an extremely slow rate. This finding would also suggest that children do not extract optic flow information like adults, which could create challenges for them in environment navigation and coordinated movement. If adultlike sensitivity to optic flow patterns and speed tuning were present during middle childhood, it would confirm that global motion processing maturation is gradual. Additionally, these findings would suggest that the infant motion processing system is distinct from that of children and adults and that this system is being restructured during childhood.

Chapter 2: Methods & Results

Participants

Thirty-three children, 21 male, 12 female, between four and eight years of age participated in the study. The mean age was 75.98 months (*SD*=17.12). The sample consisted of children drawn from a database of families in a region of Central Pennsylvania who have chosen to participate in research and who responded to advertisements by the laboratory. Children were not allowed to participate in the study if they were born prematurely, had a history of serious visual or medical problems, epilepsy or seizures. Parents were asked about epilepsy and seizure history in the initial contact phone call and during the consenting portion of the session. All children tested had normal pattern vision as evaluated with Teller Acuity Cards.

Procedures

Upon arrival to the laboratory, the study and visit was explained in detail. Next the family was shown a *HydroCel Geodesic Sensor Net* to help the child and parent(s) understand what the child would be wearing for the visit. Following this, both parent and researcher signed the consent form. Children 6 or older also signed an assent form, which was read to the child before a signature is obtained. After consent/assent, each child underwent a brief vision screen (Teller Acuity Cards) to test visual acuity. To select an appropriate *HydroCel Geodesic Sensor Net*, the child's head circumference was measured and the reference point *Cz* was marked on the center of the head using a non-toxic grease pencil. The net was soaked in an (KCl) electrolyte solution for 5 minutes and then placed on the participant. Participants were escorted to the testing room and seated on an adjustable chair 60 cm from an RGB computer monitor. Electrode impedances were checked, and once impedances met testing criteria, lights were dimmed and the

session began. Participants were allowed to take short breaks between stimulation sets. The entire testing session took about 45 min.

Stimuli

Participants viewed random-dot kinematograms generated via PowerDiva Video software (version 3.4, Smith-Kettlewell Eye Research Institute). The display consisted of 12.4 arc minute white dots on a black background at a dot density of 10%. The displays alternated between globally coherent and globally incoherent motion every .833 s, or at a frequency of 1.2Hz (See Figure 2). Incoherent and coherent motion is determined by the percentage of dots are moving in the same direction and speed. A display with a coherence level of 100% consists of all dots moving in the same direction, while a coherence level of 0% has all of the dots moving in random directions. Three types of global motion patterns were displayed; left and right rotation, left and right translation, and radial expansion and contraction. In order to reduce dot density and luminance artefacts, all patterns were displayed behind an annular mask. The mask blocked the central 4.77 deg, but showed motion in an annular ring 24 deg in diameter. These patterns were shown at three speeds: 2, 4, and 8 deg/s, forming a total of nine conditions in the block-design study. A sequence of 10 coherent and incoherent motion phases was presented in trials lasting 12 seconds. Approximately 4 to 10 trials per condition were collected contingent on participant comfort and compliance.

EEG Collection

A 128-channel *HydroCel Geodesic Sensor Net* (Electrical Geodesics, Inc.) was used in conjunction with NetStation software to record brain activity. All electrodes were maintained at or below 50k Ω . EEG was sampled rate of 1,000 Hz, referenced to Cz, and the signal was low-pass filtered at 50 Hz (Fesi et al., 2011) prior to analysis. Stimulus (coherent/incoherent) cycles that exceeded of 60 μ V were rejected as artifact. Trials that had 15% of cycles rejected by these criteria were excluded from analysis. Children who produced fewer than 3 trials per condition were also excluded. A total of 10 children were excluded from analysis; 4 were excluded due to too few trials; 4 were excluded for too many rejected cycles; 2 were excluded due to equipment malfunction. In total twenty-three children were included in the analysis, mean age 76.80 months (*SD*=18.62) (see Figure 16).

Analysis

Consistent with steady-state visual evoked potential (SSVEP) techniques, data analysis focused on the phase-locked amplitude of responses over occipital, parietal, and temporal leads at the fundamental frequency (1F=.83 Hz) following methods used previously (Gilmore et al., 2007; Hou et al., 2009; Fesi et al., 2011). PowerDiva Host 2.9 software was used offline to analyze the cortical activity related to the display of the stimuli. Topographic plots were created with mrCurrent, a Matlab-based package. In addition, phase-locked coherent averages of activity from specific electrode aggregates (left lateral, left medial, medial, right medial, right lateral) along the occipital region (see Figure 3) were created for subsequent statistical analyses. Uni- and multivariate analyses of variance (ANOVA/MANOVA) were conducted using SPSS v.20. Posthoc tests of individual means employed the Bonferroni correction for multiple comparisons.

Results

For the majority of the conditions, children's responses at the harmonic of interest (1F1) were statistically above noise. Topographic plots of some of these responses are shown in Figures 7, 11, and 15, for each group and condition. Figures 4-6, 8-10, and 12-14 show the SSVEP responses at 1.2 Hz for each condition per age group.

A multivariate analysis of variance was completed for the responses at the 1F1, with amplitude and scalp region as dependent variables. The effects of pattern F(4, 14070) = 33.56, p < .0001, speed F(4, 14070) = 7.50, p < .0001, and age F(44, 14070) = 114.81, p < .0001, were significant. Also significant were the following interactions: pattern*speed, F(8, 14070) = 7.55, p < .0001, speed*age F(88, 14070) = 8.62, p < .0001, pattern*age F(88, 14070) = 8.01, p < .0001, and pattern*speed*age F(176, 14070) = 8.23, p < .0001 (See Figure 17).

Multiple pairwise comparisons showed the magnitude of differences in response amplitudes when pattern, speed, and age group were varied. For pattern type, amplitude responses were significantly different at p = .05, with translation patterns eliciting lower responses than both radial and rotational patterns. For speed, amplitude response were significantly different at p = .05, for displays of 2 deg/s (as compared to 8 deg/s, with responses lower for the slower speed). There was also a significant difference between 4 deg/s and 8 deg/s, with the faster speed yielding a higher cortical response.

Mean amplitude responses based on age group were all significantly different at p = .05, with the youngest children showing responses higher than both the middle and oldest ranges.

The oldest children had the lowest amplitude responses overall (See Figures 4-6, 8-10, and 12-14).

In the pattern*speed interaction, cortical responses for radial motion at 2 deg/s were significantly lower at p=.05 than responses to radial motion at 8 deg/s but higher than those for translation at 4 deg/s (See Figures 7,11, and 15). Peak amplitude responses for radial 4 deg/s, were significantly smaller than those for radial 8 deg/s and rotation 4 deg/s at p=.05. Radial 8 deg/s amplitude responses were significantly greater than rotation 2 deg/s, translation 2 deg/s, translation 4 deg/s, and translation 8 deg/s at p=.05 (See Figures 4-6, 8-10, and 12-14).

Cortical response amplitudes to rotation at 2 deg/s were significantly lower than those to rotation at 4 deg/s. For the middle speed, rotation 4 deg/s responses were significantly greater than response to translation patterns at 2,4, and 8 deg/s at p=05. A similar response was found for rotation 8 deg/s, with responses greater than translation 2 deg/s (p=.05) as well as at the faster speeds. Overall, the radial pattern at the highest speed yielded the most robust responses, while the translation pattern at all speeds showed the weakest responses.

In terms of the speed*age interaction, at 2 deg/s the middle age range's amplitude responses are significantly lower than those of the youngest age range at all 3 speeds (p=.05). However, this group's responses are significantly higher than those in the oldest age group at the same speed (p=.05). At the slowest speed, the oldest age range has responses that are significantly lower than the youngest age range at all 3 speeds, the middle age range at 4 and 8 deg/s(p=.05). This group also had significantly lower responses in the slow speed condition compared to itself in the 4 deg/s condition (p=.05) and the 8 deg/s condition. For the youngest age range at 2 deg/s, they showed cortical responses that were significantly larger than those of the middle and oldest age ranges at both 4 and 8 deg/s at p=.05 as well.

At the medium speed, the middle age range shows amplitude responses that are significantly lower than those of the youngest age range at both 4 and 8 deg/s (p=.05) (See Figures 4-6, 8-10, and 12-14). The oldest age range at 4 deg/s exhibits the same trend with amplitude responses that are smaller than the youngest age range at these same speeds. For 4 deg/s, the youngest age range shows responses that are significantly greater than the oldest age group's at the highest speed (p=.05). For the 8 deg/s condition both the middle and oldest age ranges had responses that were significantly lower than those of the youngest age group at the same speed (p=.05). These results indicate that the youngest age range tends to have the most robust responses of the children at all speeds. Additionally, the slowest speed tends to yield responses that are weaker than the faster speeds.

The pattern*age interaction showed that for the radial pattern the youngest age range children show significantly greater activation (p=.05) than the older children in this sample on all 3 patterns as well as themselves for the translation. Children in the middle age range had responses that were significantly greater than themselves and the oldest range for translation, while the older children showed responses that were only significantly more robust than their responses to translation (See Figures 4-6, 8-10, and 12-14).

For the rotation pattern, the oldest age range had cortical responses that were significantly less than the youngest children for all three pattern types, but greater than themselves for translation (p=.05). With the rotation pattern, the middle age range also showed responses that were significantly greater than the oldest group's for translation. These children also had responses that were significantly lower than the youngest children's for the radial and rotation patterns. The youngest age range had responses that were significantly greater than all groups for all patterns except themselves for the radial pattern. In the translation condition, the youngest age range had responses that were significantly greater than the oldest age range's for all three patterns as well as the middle age range's for translation. This group also showed responses that were significantly lower themselves for the radial and rotation patterns (p=.05). The oldest children showed responses that were significantly lower than all other children for all patterns and themselves for radial and rotation patterns. For the middle age range, their responses were also significantly greater than the oldest group's for translation, yet significantly lower than themselves for the radial pattern and the youngest age range's for all three patterns.

These results suggest that, the oldest children have the weakest activation to translation patterns out of all the age ranges, while the youngest children tend to have the most robust activation for all patterns. The findings also indicate that both radial and rotation patterns yield robust responses for all children in the sample, while translation shows the least robust activation.

For the 3 way interaction of pattern*speed*age, radial motion at 2 deg/s the middle age range's activation was significantly greater than the oldest age range's for: radial 2 deg/s, rotation 2 deg/s, and translation 4 and 8 deg/s (p=.05). For this same condition, this group had responses that were significantly lower than those of the youngest group for: radial 2 and 8 deg/s as well as rotation 2 and 8 deg/s (p=.05). In the slowest condition for radial motion the oldest age range showed activation that was significantly lower than youngest group for: radial 2,4, and 8 deg/s, rotation 2,4, and 8 deg/s, and translation 2 and 4 deg/s (p=.05). This group's activation was also significantly lower than middle group for: radial 4 and 8 deg/s, rotation 4 and 8 deg/s, and translation 8 deg/s, rotation 4 and 8 deg/s, rotation 4 and 8 deg/s, and translation 8 deg/s (p=.05). In comparison with itself this age range's showed lower activation than in the following: radial 8 deg/s, rotation 4 deg/s (p=.05). The youngest age range

showed significantly greater activation in this condition than the middle and oldest age ranges' at the following: radial 4 and 8 deg/s, rotation 2 and 8 deg/s, and translation 2,4, and 8 deg/s (p=.05). Compared to itself, this group also showed significant greater responses than those in the translation 8 deg/s and radial motion 4 deg/s condition (p=.05) (See Figures 4-6, 8-10, and 12-14).

For radial motion at 4 deg/s, the middle age range displayed significantly lower activation than the youngest age range's for: radial 8 deg/s and rotation 2 and 8 deg/s (p=.05) (See Figure 4,5, and 8). Their activation was significantly greater than the oldest age range's for translation at 4 deg/s. At 4 deg/s the oldest children had responses that were significantly lower than the youngest age range's at: radial 8 deg/s, rotation 2 and 8 deg/s, and translation 4 deg/s (p=.05) (See Figures 4-6 and 12). Responses were also significantly greater than this groups for translation 4 deg/s, but significantly lower than those for rotation 4 deg/s (p=.05). At the middle speed the youngest age range had responses that were significantly higher than those of the oldest age range's at rotation 2 deg/s, and translation 2, 4, and 8 deg/s (p=.05) as well as the middle group for translation at 4 deg/s. Their amplitude responses were also lower than their means for radial 8 deg/s and rotation 2 and 8 deg/s (p=.05).

The middle age range at the highest speed for radial motion showed greater cortical responses than the oldest age range's for the following conditions: rotation 2 deg/s, and translation 4 and 8 deg/s (p=.05) (See Figure 11). This group's responses were also significantly lower than the youngest children's for: radial 8 deg/s and rotation 2 and 8 deg/s (p=.05). At 8 deg/s the oldest children had responses that were significantly lower than the younger group for radial and rotation patterns at 8 deg/s (p=.05). Compared with itself, this group showed greater activation in this condition than for translation 2,4, and 8 deg/s and rotation 2 deg/s (p=.05) (See

Figures 8-10). They also showed significantly greater activation than the middle group for translation 4 deg/s. In the fastest speed condition the youngest children had amplitude responses that were significantly higher than middle group for: rotation 2, 4, and 8 deg/s, and translation 2, 4, and 8 deg/s (p=.05). Their responses were as significantly higher than those of the oldest age range's for: rotation 2 and 8 deg/s, and translation 2, 4, and 8 deg/s (p=.05). Compared to itself, this group's responses were also significantly higher than those for: rotation 4 deg/s, and translation 2, and 8 deg/s (p=.05) (See Figures 4-6).

These results suggest that radial patterns at the fastest speed tend to yield the most robust cortical responses for all groups. The youngest children also tend to have larger cortical responses than all the groups for most conditions. The translation pattern at all 3 speeds for each age group also elicits the weakest activation (See Figures 6, 10, and 14).

Chapter 3:

Discussion

For this sample of children, the results indicate that cortical evoked responses to translation patterns are weaker than those to radial and rotational patterns. This coincides with adult data from previous work, which showed that adults had larger peak amplitude responses for radial motion versus translational motion (Gilmore et al., 2007). It further suggests that adult-like sensitivity to patterns of optic flow consistent with locomotion through space emerges between early infancy, when linear patterns dominate, and early childhood. Our results also show that children's cortical responses were lower for slow speeds as compared to fast speeds. These findings align with adult data and suggest that at some point during middle childhood, children begin to exhibit optic flow sensitivity that is similar in some respects to adults.

There were also group differences in peak amplitude responses, with the youngest age group having the highest responses. Differences in these responses may also reflect physical changes. Children's skulls tend to be thinner than adults, thus they show higher mean amplitude responses than adults. These amplitude differences may indicate growth of the skull. Results also indicated that the radial motion condition at the fastest speed yielded the most robust results, as previous research with adults has shown (Fesi , 2012).

The 4 and 5-year-olds showed the most robust responses to all of the speeds, while the 6, 7, and 8-year-olds had the strongest responses to the higher speeds. These findings indicate that as the visual system matures, cortical responses become tuned for faster speeds. All age groups showed robust responses to radial motion at the highest speed; this was especially true for the oldest age group which had the strongest cortical responses to this condition. Although the youngest age group's activation to translation was not more robust than radial at 8 deg/s, their responses were significantly greater than the other groups' for translation. These findings indicate that during middle childhood, children's cortical responses become tuned for patterns that adults respond robustly to, particularly radial motion. These findings and those from Fesi et al. (2012) contradict the previous research by Hou et al. (2009) in which adults showed higher amplitude responses to slow speeds (< 4 deg/s) relative to fast. Hou et al. (2009) examined rotational flows only, and the speed tuning response was shown largely over the midline (Cz) electrode. These details may explain part of the apparent contradiction. A close examination of the tuning curves in this study indicates that the youngest children show the largest amplitude responses to rotational patterns at 8 deg/s, but that older children show peak responses to rotation at the slower, 4 deg/s speed. Thus, the predicted fast-to-slow developmental trend observed previously may be limited to a particular pattern type -- rotation. Furthermore, the Hou et al. study used a low density/low impedance electrode array. The current study used a high density array, and collapsed across a set of channels to approximate the low density montage. It is possible that this difference in recording technique or the choice of channels used in creating the low density comparison montage account for some of the discrepancies between the studies.

Much research demonstrates that the primate visual system develops gradually over time (Ellemberg et al., 1999, Kiorpes et al., 2004; Gilmore et al., 2007; Hou et al., 2009). Among the later maturing features is sensitivity to optic flow. Global motion perception, and optic flow in particular, are important for individuals when navigating through the environment and thus have important real world implications (Gibson, 1950; Plumert et al., 2007; Britten, 2008). To date, there is much information about infant and adult optic flow sensitivity; however there is a gap in

the literature pertaining to the development of children's responses to optic flow. The current study sought to explore when optic flow sensitivity reaches adult levels. The results indicate that around middle childhood sensitivity to optic flow patterns appears much more like that of adults than infants. On the surface, these differences may appear to be age-related but they most likely reflect variation in levels of functional maturity in the developing visual system. Given that all of the children's responses are not yet adult-like, particularly electrode aggregate group activation, this provides support for the idea that the visual system restructures itself from infancy to adulthood.

There are important real-world implications for understanding global motion processing across development. Successful navigation requires the accurate perception of objects, surfaces, and patterns of movement in the environment (Britten, 2008; Plumert, Kearney, & Cremer, 2007). Parrish and colleagues (2005) suggest that motion processing abilities are vital for locomotion, crossing streets, as well as catching and throwing. Road crossing is one real-world situation that that engages children's developing visual system. Children tend to overestimate physical abilities in road crossing and make errors in perceiving how their abilities fit in with the properties of the environment; they show a delay in movement initiation for road crossing compared to adults, and younger children (5-year-olds) often accept non-safe gaps in traffic more so than older children (12-year-olds) (Connelly, Conaglen, Parsonson, & Isler, 1998; Plumert, Kearney, & Cremer, 2004; Plumert, 1995, Plumert & Schwebel, 1997). Plumert et al. (2007) attribute these errors to children's inability to rapidly couple their motor movements with the perceptual information they are receiving. Additional research on road crossing has also indicated that there are developmental differences in sensitivity to vehicular looming (Wann, Poulter, & Purcell, 2011). Slow vehicles loom more than fast vehicles, thus a vehicle traveling at a fast speed may appear as if it is not approaching. Studies with macaques have found the area MSTd is important for detecting looming objects (Tanaka & Saito, 1989). If a similar region is responsible for the same task in the human brain, but the visual system is still organizing in childhood this could mean that this area is not functionally mature. This could be related to the problems seen with children and road crossing. Perceptual tests indicate that children may not be able to perceive a vehicle as approaching if it is traveling over 20 mph, which leaves them more vulnerable to traffic-pedestrian accidents. Atchley and Andersen (1998) found that older individuals' sensitivity to radial flow declined when retinal eccentricity increased, indicating detection of motion in the periphery. Since the visual system is still developing in childhood it is possible that children are experiencing this same deficit. Future studies should explore children's motion and form processing in the periphery to help understand these issues. Uncovering what is occurring in children's perception of motion throughout development could help prevent against children's dangerous decisions when road crossing.

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Translation

Rotation

Radial

Figure 1 Optic Flow Patterns.



Figure 2 Global motion display.



Figure 3 Electrode aggregate groups.



Figure 4 4-5-year-olds peak amplitude responses (µV) to radial pattern at 3 speeds(deg/s).



Figure 5 4-5-year-olds peak amplitude responses (μ V) to rotation pattern at 3 speeds (deg/s).



Figure 6 4-5-year-olds peak amplitude responses (μV) to translation pattern at 3 speeds(deg/s).



4-5-Year-Olds Topographic Plots

Figure 7 4-5-year-olds topographic plots for 3 patterns and 3 speeds.



Figure 8 6-year-olds peak amplitude responses (μV) to radial pattern at 3 speeds (deg/s).



Figure 9 6-year-olds peak amplitude responses (μV) to rotation pattern at 3 speeds (deg/s).



Figure 10 6-year-olds peak amplitude responses (μ V) to translation pattern at 3 speeds (deg/s).



6-Year-Olds Topographic Plots

Figure 11 6-year-olds topographic plots for 3 patterns and 3 speeds.



Figure 12 7-8-year-olds peak amplitude responses (μV) to radial pattern at 3 speeds (deg/s).



Figure 13 7-8-year-olds peak amplitude responses (μV) to rotation pattern at 3 speeds (deg/s).



Figure 14 7-8-year-olds peak amplitude responses(μV) to translation pattern at 3 speeds (deg/s).

7-8-Year-Olds Topographic Plots



Figure 15 7-8-year-olds topographic plots for 3 patterns and 3 speeds.



Figure 16 Distribution of ages (in months) in sample.

Effect	F	df	Error df	Sig
Pattern	33.56	4	14070	.000
Speed	7.50	4	14070	.000
Age	114.81	44	14070	.000
Pattern*Age	8.01	88	14070	.000
Speed*Age	8.62	88	14070	.000
Pattern*Speed	7.55	8	14070	.000
Pattern*Speed*Age	8.23	176	14070	.000

Multivariate Tests

Figure 17 Multivariate tests statistics.