A high-density EEG study on cortical activity in response to visual motion perception: Longitudinal comparison of preterm and full-term infants

by

Belde Mutaf

October 2012

Developmental Neuroscience Laboratory

Department of Psychology

Norwegian University of Science and Technology

Trondheim, Norway

This Master's thesis will be submitted to an international journal in the near future in approximately its current form.

TABLE OF CONTENTS

ACKNOWLEDGEMENTS

Trondheim, October 2012
Belde Mutaf

ABSTRACT

Electroencephalogram (EEG) was used to investigate brain electrical activity of full-term and preterm infants at 5 and 12 months of age as a functional response mechanism to structured forwards optic flow, structured reversed optic flow, and random visual motion. EEG data were recorded with a 128-channel sensor array and visually evoked potentials (VEPs) were analysed. VEP results showed a significant improvement in full-term infants with age in latencies to forwards and reversed optic flow, but not to random visual motion. In addition, full-term infants at 12 months significantly differentiated between the three motion conditions. They showed the shortest latency to forwards optic flow and the longest latency to random visual motion. On the other hand, preterm infants did not improve their latencies with age, nor were they capable of differentiating between the three motion conditions at 12 months. It appeared that full-term infants at 12 months with a substantial amount of self-produced locomotor experience and accompanying neural maturation, rely on the perception of structured optic flows to move around in the environment efficiently, and that they are negatively affected by the lack of structure in random visual motion. It was concluded that the preterm infants' poorer performances are related to impairment of the dorsal visual stream which is specialized in processing visual motion. To better understand the fundamentals of early neurodevelopment and how it differs in prematurity, more research comparing data on the changes in brain activity in response to visual motion perception during infancy is suggested.

1.0 INTRODUCTION

A huge number of daily activities including social interaction with other people, accurate face perception, and cognitive skills such as object categorization, reading a book, and navigating through a cluttered environment first of all depend on perception and correct interpretation of visual information (van den Boomen, van der Smagt & Kemner, 2012). Considering the sequence and importance of these abilities, a developmental perspective is needed to understand how an individual learns to make use of relevant visual information for perception. Understanding neurodevelopment has also clinical importance given that many neurological and psychiatric disorders are associated with abnormal early developmental factors. One of the factors having received considerable interest is premature birth with its continuously increasing incidence (Martin, Hamilton, Sutton, Ventura, Menacker, et al., 2003).

Among the daily activities, ego motion is considered to be a very basic skill by many people, yet moving around the environment requires a great deal of effort in the brain. One of the complex tasks of the brain is to recognize the landmarks in the environment and their egocentric positions which are identified as being relative to us and then combine all the information. The compositions where the major images emanate from a central point within our angle of sight in a structured form are referred to as radial flow. As defined by Gibson (1979), the total change of scenery either by locomotion in any direction or as an object approaches a person is called 'optic flow'. The visual motion perception that is achieved by this change is crucial for the purposes of adjusting posture, calculating the exact time-to-contact for any movement (van der Weel, van der Meer & Lee 1994; Kayed & van der Meer, 2009), reaching a target efficiently by heading (Lappe, Bremmer & van den Berg, 1999; Turano, Yu, Hao & Hicks, 2005), and avoiding obstacles on our path (Wilkie & Wann, 2003). The relation between optic flow perception and action has often been studied in terms of motor activities (Warren, Kay, Zosh, Duchon & Sahuc, 2001; Bruggeman, Zosh & Warren, 2007). It has been proven that optic flow perception has a significant control on walking direction (Bruggeman & Warren, 2010) and speed (Lamontagne, Fung, McFadyen & Faubert, 2007). Lamontagne et al. (2007) also reported that stroke patients have impaired modulation of gait speed in case of changes in the perception of movement with different optic flow speeds. Additionally, action-to-perception transfer, or improvement in visual perception by actual motor learning has been

reported (Beets, Rösler & Fiehler, 2010). However, young infants are not as efficient as adults in detecting optic flow (van der Meer, Fallet & van der Weel, 2008).

Given the importance of radial flow for visual motion perception, rudimentary perception of optic flow patterns appears within the first weeks and months after birth (Gilmore, Baker & Grobman, 2004), whereas adults can readily distinguish between expansion/contraction, rotation (left and right), and translation (horizontal and vertical) of motion (Gilmore, Hou, Pettet & Norcia, 2007). EEG studies showed that infants younger than 6-8 weeks old do not discriminate motion direction, and do not smoothly pursue small moving objects. However, around 6 to 14 weeks infants' ability to discriminate motion direction and to follow moving objects with their head and eyes improves rapidly (Rosander, Nyström, Gredeback & Von Hofsten, 2007). In a literature survey, Shirai and Yamaguchi (2010) reported that the motion patterns mentioned above display unique developmental trends. For instance, perception of single directional motion emerges at approximately two months of age whereas perception of radial motion and its cortical responses develop rapidly thereafter, starting just before three months until approximately four months. Interestingly, the ability does not change significantly between four to eight months of age. Thus, the fast perceptual development starts decelerating after the first few months (Fielder, Harper, Higgins, Clarke & Corrigan, 1983), and it approaches adult level by the age of four years at the earliest (Kaufmann, 1995). Shirai and Yamaguchi (2010) also reviewed the developmental interaction of defensive motor responses and visual radial motion, reporting that infants younger than one month of age exhibit defensive responses such as backwards head tilting or frequent blinking. However, these responses were interpreted as a reaction to a combination of simple physical properties included in a structured radial motion instead of the motion perception per se. Moreover, neonates as young as three days old were observed to be sensitive to optic flow, as they leaned their head backwards when they were exposed to backwards flow stimuli. In addition, the mean head pressure was found to be linearly increasing with the velocity of the optic flow. These kind of defensive responses were interpreted to be the result of multimodal integrative and cooperative processes in which visual, vestibular and proprioceptive senses were involved (Jouen, Lepecq, Gapenne & Bertenthal, 2000).

Various brain imaging studies on both humans and other primates have investigated the responsible cerebral network in the brain specialized for perception of visuo-spatial information. Studies have agreed upon the *dorsal visual stream* where neurons from the

primary visual cortex reach to the medial temporal (MT) and medial superior temporal (MST) areas, together known as V5/MT+ (Newsome & Paré, 1988; Greenlee, 2000; Riecansky, 2004; Smith, Wall, Williams & Singh, 2006). In particular, perception of control of movement including self-motion and motion of objects is executed by the dorsal visual stream (Creem & Proffitt, 2001). Neurons within the MT area are sensitive to directionality whereas the MST area is involved more in the perception of motion (optic flow analysis) (Smith et al., 2006; Wall, Lingnau, Ashida & Smith, 2008a). From the V5/MT+ region, information passes to the parietal cortex for the analysis of spatial relations between objects and the observer (Greenlee, 2000). The V5/MT+ area is also excited by unconscious motion perception when the stimulus is presented implicitly (Itoh, Fujii, Kwee & Nakada, 2005).

The human brain is a complete network of about 100 billion neurons and 100 trillion synapses. The brain structures are connected to each other so that we are capable of exhibiting complex behaviours. Counsell and Broadman (2005) stated that preterm birth causes differential brain development that is evident from abnormalities in tissue microstructure and cerebral morphology measured with MRI (Magnetic Resonance Imaging). Some of the manifesting dysfunctions of preterm birth have been related to attentional, cognitive, and behavioural impairments (Bhutta, Cleves, Casey, Cradock & Anand, 2002; Salt & Redshaw, 2005; Johnson, 2007; Aarnoudse-Moens, Weisqlas-Kuperus, van Doudoever & Oosterlaan, 2009; Delobel-Ayoub, Arnaud, White-Koning, Casper, Pierrat, et al., 2009; de Jong, Verhoeven & van Baar, 2012). At this point, understanding the impairments in visual motion perception development is as important as understanding normal development in order to contribute to an explanation of many disorders. Therefore, early motion perception performances have also been investigated in terms of prematurity, since pre-term birth is considered to be at high risk for neuro-developmental disorders. In answer to the studies that examined whether the deficits in motion and form perception are caused by prematurity per se (MacKay, Jakobson, Ellemberg, Lewia, Maurer, et al., 2005) or by possibly accompanying periventricular leukomalacia (PVL) (Downie, Jacobson, Frisk, & Ushycky, 2003; Jacobson, Frisk, & Downie, 2006), Guzzetta et al. (2009) reported a difference between global motion (optic flow) and form information perception (shapes, outlines) in a behaviourally assessed experiment. Preterms both with and without brain damage performed worse than full-term controls in global motion perception, however when form information was embedded in the stimuli, pre-terms with PVL performed worse than preterms without PVL. The

outcome of the study suggested impairment of the dorsal stream visual processes in preterm children without brain damage. In four cohort studies in which several assessment techniques were used and the correlations between the results and MRI indications for brain abnormalities were analysed, Atkinson and Braddick (2007) also pointed to impairment of the visual dorsal stream as a cause for the cluster of developmental problems seen in children born prematurely. The findings were supported in studies where global motion, global form, and biological motion (combination of form and motion cues) perception were compared in preterm children. Results showed that global motion perception deficit is observed more densely than global form deficit, and difficulties in biological motion perception were also present but to a lesser degree (Taylor, Jakobson, Maurer & Lewis, 2009). Additionally, disruption level in perception of global motion was greater between mild/moderately and severe white matter damaged preterm infants in global motion processing (Atkinson, Birtles, Anker, Braddick, Rutherford et al., 2008a). Furthermore, in all tasks the preterm group performed with decreased visual sensitivity. When motor skills were tested, preterm born children between 7 and 11 years of age performed less accurately or slower in a pointing movement task which implies less efficient elementary visuomotor processes suggesting the impaired dorsal visual stream functioning (van Braeckel, Butcher, Geuze, van Dujin, Bos, et al., 2010).

The research above was all carried out with school-aged children, yet it is also important to clarify the developmental progress of possible abnormalities at younger ages to provide early indicators of brain damage. In a number of well-designed studies, Atkinson and her colleagues have formulated specific 'markers' of visual cortical function in the first postnatal months for both normally and atypically developing infants for the purpose of setting diagnostics of early brain damage. One of the markers measured orientation-reversal visual event-related potentials (OR-VERP) (Braddick, Wattam-Bell & Atkinson, 1986; Atkinson, Hood & Wattam-Bell, 1992; Braddick, 1993; Braddick, Birtles & Wattam-Bell, 2005), and the other measured cortical control of visual attention through fixation shifting under competition (FS) (Atkinson, et al., 1992; Braddick, Atkinson & Hood, 1992). A subsequent study confirmed that the severity of detected brain injury by MRI in preterm infants was correlated with impaired OR-VERP and FS results, and preterm infants displayed worse performance on the cortical tests (Atkinson, Braddick, Anker, Nardini, Birtles, et al., 2008b). However, still more data on full-term and preterm infants are needed, and the present study will contribute to filling the gap.

During a visual perception task the electrical activities of cortically dominant pyramidal neurons are recorded by EEG in a millisecond timeframe with high temporal and spatial resolution (Tucker, 1993). Motion sensitive visually evoked potentials (VEPs) originate from V5/MT+ which corresponds to occipital and parietal areas that lie in the posterior part of the brain, and they are characterized by the negative peak component N2, which occurs around 180 - 220 ms post stimulus in 8-month-old infants (van der Meer, et al., 2008), and around 150 to 200 ms post stimulus in adults (Fielder et al., 1983). The peaks' amplitude and latency features of the electrical activity in the brain in response to visual motion have been in the centre of investigation for years. Those characteristics inform us about the effort and time that have been used to process the motion stimuli. Previous studies reported that the early visual components in infants are longer in latency and higher in amplitude compared to adults based on the peak N2 (van der Meer et al., 2008). Similar results have been shown for N1 and P2 peaks, namely decreasing latencies as children grow older (Fielder et al., 1983).

It has been found that posterior parietal cortex selectively gets activated by structured radial optic flow patterns (Kobayashi, Yoshino, Kawamoto, Takahashi & Nomura, 2004; Wall & Smith, 2008b). In an experiment on cortical responses to optic flow, Gilmore et al. (2007) compared motions of expansion/contraction, rotation, and translation. The highest amplitude responses for adults were found for expansion/contraction over central channels, especially O1, Oz, and O2. They observed marginally significant responses to the translation display over Oz, O2, and PO8, and to rotation over PO8. Hou, Gilmore, Pettet & Norcia (2009) investigated the responses of spatiotemporal tuning of coherent motion stimuli. Consistently, the findings for adults showed that tuning functions were similar at O1, Oz and O2 derivations, but different at PO7 or PO8. In a similar study van der Meer et al. (2008) analysed channels O2, PO10, Iz, and O10 in adults and channels PO3, POz, O1, Oz in infants on the N2 component. They found shorter latencies for structured optic flow than for random visual motion in both adults and infants. Additionally, infants' responses to visual motion revealed longer latencies, particularly for random visual motion, and larger amplitudes than those for adults.

The present study aimed to explore the development of the visuo-cognitive systems, especially visual motion perception in the brain during early infancy with a focus on the effects of prematurity. Longitudinal data allowed comparison of the preterm and full-term infants at the ages of 5 and 12 months. VEPs to motion perception were analysed in order

to describe the differences or similarities between groups, and to develop a criterion for possible diagnostic purposes as well. It was expected that perception of forwards and reversed optic flow would rapidly improve with increasing age as shown by shorter latencies due to neural maturation and increased locomotor experience, while no such difference would be observed in perception of random visual motion. Differences between preterm and full-term infants' perceptual abilities towards the three motion conditions at both ages were also explored so as to investigate whether poor differentiation could be indicative of brain damage in the preterm group.

2.0 METHODS

2.1 Participants

Ten preterm and ten full-term, normally developing infants were recruited for the study. The preterm babies were recruited with the help of the paediatrician in charge of the Neonatal Intensive Care Unit at St. Olav's University Hospital (Trondheim, Norway). The preterm infants included in the study were born at ≤ 33 weeks of gestation with birth weight ≥ 1000 g, and they did not have any major factors (such as severe brain damage, retinopathy of prematurity (ROP) and/or other perinatal issues requiring serious medical interventions) leading to abnormal development. However, experimenters were unaware of the infants' neurological status, birth history and any events during their stay at the hospital. The full-term babies were recruited either by contacting the parents through birth announcements in the local newspaper, or by parents' own willing and request for their baby's involvement in the study.

Preterm and full-term infants were matched according to their age in full months. To attain a valid matching, age corrected for prematurity was calculated for the preterm babies. However, one of the preterm babies was very uncomfortable during the second testing when he was 12 months old and this precluded the experimenters to collect any data on him; therefore, he had to be excluded from the longitudinal analysis. As a consequence, his matched full-term control was excluded automatically as well. Thus, longitudinal analyses were performed on 18 infants in total for both testing sessions.

For the first session, the mean (corrected) age of the preterm infants was 4 months and 26 days (SD = 6.9) with a range of 139–158 days, and the mean age of the full-term infants was 4 months and 16 days (SD = 21.3) with a range of 111–164 days. For the second session, the same preterm infants' mean age was 12 months and 18 days (SD = 18.6) with a range of 356–414 days, and the same full-term infants' mean age was 11 months and 20 days (SD = 13.9) with a range of 333–371 days. Full-term infants had a history of crawling acquisition at around 9 months. Two of them were able to walk independently at the time of the second testing, whereas the others with the exception of one were all able to pull to stand and cruise while holding on. Motor development of the preterm infants was similar to that of the full-term infants, except for three of the preterm infants who had not started crawling or pulling to stand at the time of the second testing, and were bottom shuffling instead.

Electroencephalography (EEG), a brain electrical activity measuring technique over the scalp is known to have no painful or harmful effects. Parents were informed about the safeness of the procedure and their right to withdraw from the testing at any time before or during the experiments, and parents signed an informed consent form on this knowledge. The study has been approved by the Norwegian Regional Ethics Committee and the Norwegian Data Services for the Social Sciences.

2.2 Experimental stimuli and paradigm

To investigate the development of motion perception generated by movement in space, the stimuli were programmed in E-Prime (Psychological software tool) and mirror-reversed projected by an ASK M2 projector onto a wide (1.1 x 0.8 m) white screen (visual angle of 68º horizontal by 47º vertical) which was placed at a distance of 80 cm from the infants. To create the motion perception in the laboratory environment, an optic flow stimulus was produced by means of a streaming black dots demonstration. The forwards optic flow condition simulated movement towards an observer, reversed optic flow simulated movement away from an observer, and random visual motion presented a scene of randomly moving dots.

The forwards optical flow condition consisted of 80 randomly placed dots (5 mm radius) on the white screen. Dots moved outward from the centre of the screen as a reference point with an exponential acceleration of 1.15 pixels per frame. Dot size increased gradually about 1/40 (0.025) pixel per pixel so as to simulate forwards motion, and they appeared to move towards the infant with a -1.8 m/s constant velocity in the z-axis while velocities in the x- and y-axis were zero (see Figure 1). To compensate for dots moving out of the aperture, all dots leaving the screen were replaced immediately. Assuming a virtual space pyramid is created from the eye to the four corners of a rectangular screen where the probability of placement for each particle at any point in virtual space was made the same for all points in the pyramid, then dot particles that moved outside the pyramid and the range of sight on the rectangular screen had an equal probability of placement when they were automatically repositioned on the screen. A red fixation point the size of one pixel was presented in each trial to attract the attention to the middle of the screen. Duration of presentation for the stimuli was 1000 ms. So as to prevent motion adaptation each motion pattern was followed by a static dot pattern lasting 1500 ms which was the frozen version of optic flow pattern with zero velocity in all

directions. The reversed optic flow condition of the study was different only in terms of the direction of dot motion. Here, dots moved inwards from the edges with the same constant but positive velocity (1.8 m/s) in the x-axis while those in the x- and y-axis were zero, and dot size decreased to create the feeling of going backwards. In the random motion condition, 80 dots moved randomly on the screen at constant velocity. The order of presentation of the three conditions was random. Lights were turned off in the experimental room in order to provide a sharper view of the screen.
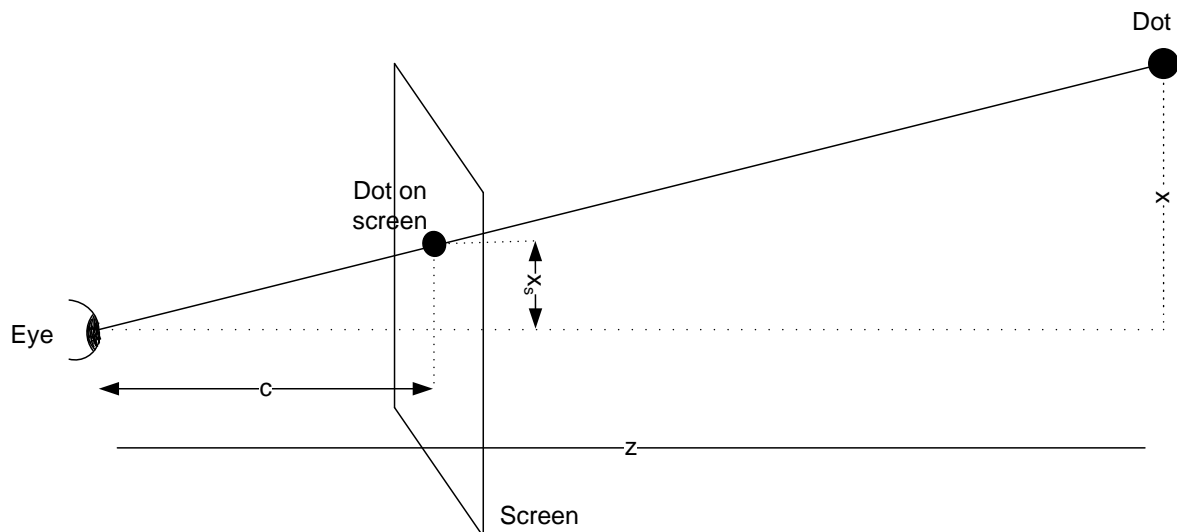

Figure 1. Schematic illustration of the projection from a three-dimensional virtual space on to a two-dimensional screen, where 'x' and 'z' are position variables, 'x_s' is the position in the x-direction, and 'c' is the constant distance (80 cm) of the infant's eye to the screen.

2.3 Data acquisition

A Geodesic Sensor Net (GSN) 200 (Tucker, 1993) provided the means of recording the EEG activity. This consisted of an array of 128 sensors that were evenly distributed on the infant's head. A high-input EGI amplifier connected to the GSN 200 ensured amplification of signals at impedance set to a maximum of 50 kΩ as recommended for an optimal signal-to-noise ratio (Budai, Contento, Locatelli, & Comi, 1995; Picton et al., 2000; Ferree, Luu, Russell, & Tucker, 2001). Net Station software on a Macintosh computer recorded the amplified EEG signals at 500 Hz. Infants' gaze was tracked using an infrared Tobii X50 camera. The visual feed was processed with Clear View software on an HP computer. To track off-line the behaviour of the infants during the experiments, digital videos were recorded with two cameras positioned at different angles in front of the infants. Recorded data were subsequently stored for off-line analyses.

2.4 Procedure

Parents arrived with their infant 10 to 15 minutes prior to the experiment. The necessary information about signing the consent form was given to the parents while the infant was allowed some time to get used to the laboratory surroundings. Infants got acquainted with the surroundings by typically playing with toys and exploring the new environment. In the process, an assistant measured the infant's head circumference to allow for the correct size selection of the GSN 200. After immersing the appropriate electrode net in a saline electrolyte solution so as to optimize electrical conductivity, it was partially dried and mounted on the head of the infant while seated on the parent's lap. The infant's attention was distracted from the net with small sounding toys and colourful soap bubbles. Immediately after mounting the net, the infant was moved into a dimly lit experimental room. The room was separated with a transparent glass partition from a control room where an assistant managed the computers necessary for the data acquisition. The infant was positioned in front of the screen while sitting on the parent's lap during the first testing session, or in a baby car seat with one parent right next to them during the second session (see Figure 2). The net was connected to the amplifier and the impedance of the electrodes was checked. If necessary, contact of electrodes was improved by adding saline electrolyte to the electrodes or simply adjusting their positions. For the entire duration of the experiment, a parent was present in the experimental room to reduce any stressful effect an absent parent may have while the presence of an assistant was required to monitor the experiment and to help the infant focus on the screen.

An experimental session began with the optic flow experiment immediately after calibrating the infant's eye movement in virtual space to the Tobii X50 camera, and was followed by looming and occlusion experiments. The optic flow experiment took about 4-5 minutes on average. In a random sequential order, generated stimuli were presented on the screen for a varying number of trials, typically 60-100 per infant. Data acquisition was carried out in one block. However, presentation was paused if an infant showed signs of disinterest or boredom at which time the assistant and/or parent played for a little while with the infant to revive the level of interest. A considerable level of disinterest, tiredness or fussiness on the part of an infant signalled the end of the experiment.

Figure 2. Actual appearance of the experimental room when the infant was 12 months, sitting in a baby car seat with one of the parents on the right side and the experimenter on the left side of the infant. The Tobii X50 eye movement tracker camera is placed on the desk in between the infant and the screen. The window behind the infant separates the control room from the experimental room.

2.5 Data analysis

EEG raw data were analysed with Brain Electrical Source Analysis (BESA) research software version 5.3 for both testing sessions. As an initial pre-processing step, recordings were segmented with the Net Station software and exported as raw files. Appropriate auxiliary files that contained trigger and sensor information were then imported and attached. Epochs around the triggers of stimuli were set such that the averaging epoch was at -200 ms to 800 ms at a baseline definition of -100 ms to 0 ms. Notch filter was set at 50 Hz to remove 50 Hz lines interference from the recorded data. Low cut-off filter was set at 1.6 Hz to remove slow drift in the data while a high cut-off was set at 60 Hz. Band pass was disabled for averaging. By visual inspection, artefact-contaminated channels and epochs resulting from head or body movements were excluded from further analyses or interpolated where necessary. In scanning for artefacts, threshold values for gradient and low signal were set at 75 μV and 0.1 μV, respectively while maximum amplitude was set

11

at 200 µV or in some few instances, at 220 µV. Since EEG signals are usually contaminated by physiological artefacts such as blinking and eye movements (Shao, Shen, Ong, Wilder-Smith, & Li, 2009; Lindsen & Bhattacharya, 2010; Pham, Croft, Cadusch, & Barry, 2011), a manual form of artefact correction (Berg & Scherg, 1994; Ille, Berg, & Scherg, 2002; Fujioka, Mourad, He, & Trainor, 2011) designed to separate brain activity from artefacts using spatial filters was further employed.

For the VEP peak analysis, data on each individual infant were averaged over whole EEG files and interpolated to 81 standard electrodes after re-referencing to an artificial reference calculated from the average potentials over the scalp such that individual averages were obtained. The individual averages for infants in each of the two sessions were then combined into grand averages for each session. The N2 components of the VEP waveforms were identified and values for peak latencies and peak amplitudes of the individual averages were recorded and subjected to further VEP analyses.

3.0 RESULTS

The mean number of accepted trials per infant across the three motion conditions for 5-month-old full-term infants was 39 (SD = 9.7, range = 31-62), and for 12-month-old full-term infants the mean number was 36 (SD = 11.7, range = 23-64). Preterm infants at 5 months of age provided an average of 44 (SD = 13.4, range = 25-73) accepted trials per infant across the three motion conditions, whereas preterm infants at 12 months of age provided an average of 38 (SD = 7.5, range = 28-53) accepted trials. The number of the trials was distributed equally among the three motion conditions.

3.1 VEP responses

For each group and each testing session, four posterior electrode channels which showed the highest N2 amplitude values in the forwards optic flow condition of the grand average VEPs were chosen for further analysis. The four grand average channels of full-term infants at 5 months were POz, O1, PO3, and PO4, and at 12 months the four grand average channels were PO4, Oz, O2, and PO8. The four grand average channels of preterm infants at 5 months were O2, POz, PO4, and Oz, and at 12 months the four grand average channels were O1, POz, PO3, and Oz. Scalp localizations of the channels are presented in Figure 3 and visually evoked waveform appearances of a channel for one of the full-term and one of the preterm infants at the two ages are presented in Figure 4.
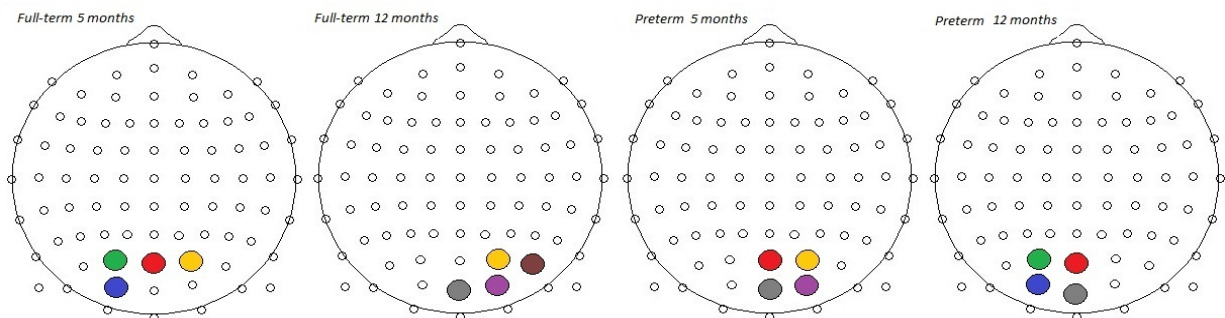

Figure 3. Scalp localization (nose up) of the 81 standard channels on top view of the head drawings with colour coded channels of interest: PO3 (green), O1 (blue), POz (red), PO4 (yellow), Oz (grey), O2 (purple), and PO8 (brown).
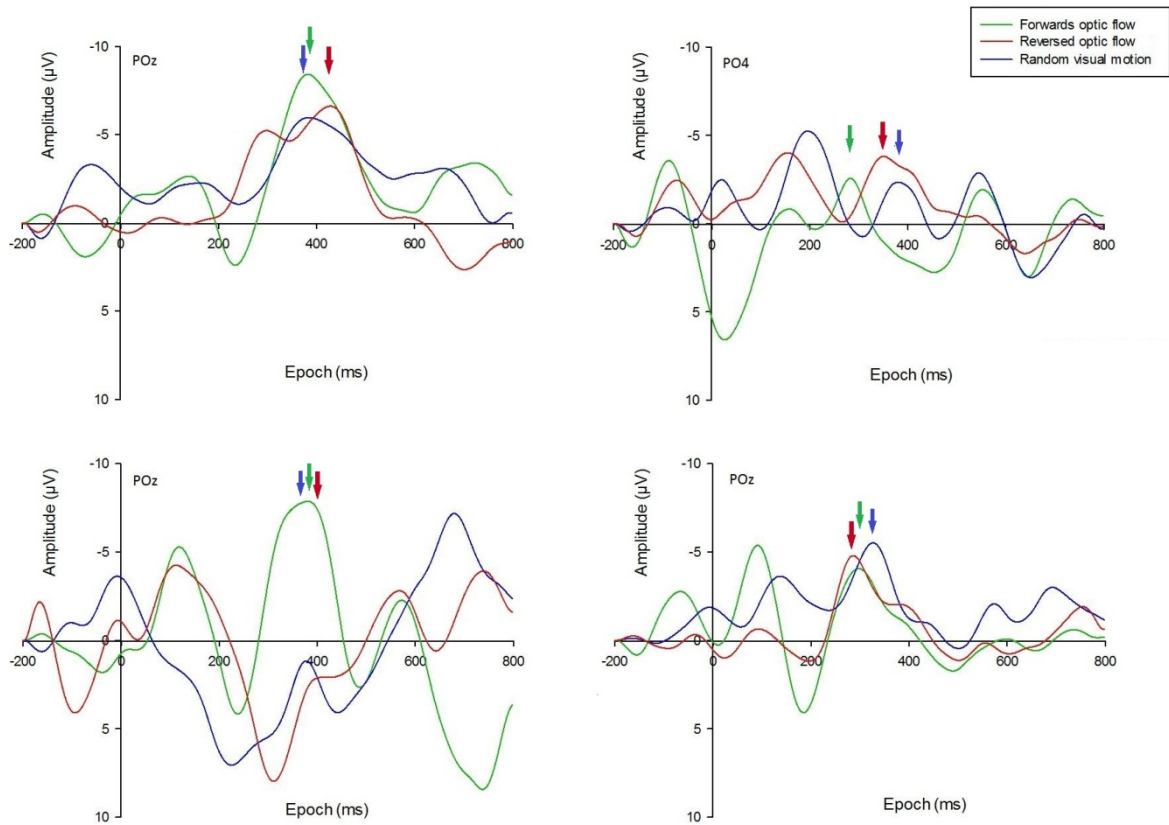
Figure 4. VEPs for a typical full-term infant at the top and for a typical preterm infant at the bottom at 5 months (on the left) and 12 months (on the right) for forwards optic flow (green), reversed optic flow (red), and random visual motion (blue). The N2 peaks for forwards optic flow, reversed optic flow and random visual motion are marked with arrows at the channels that are noted.

3.1.1 Latency analysis of VEPs

Latencies of the VEPs were analysed separately using repeated measures ANOVAs in a 2 (group) X 2 (age) X 3 (motion condition) factor design. Within subject factors were motion condition (forwards optic flow, reversed optic flow, and random visual motion) and age (5 and 12 months), while between subject factor was participant group (full-term and preterm). Adjustment for multiple comparisons was made by Bonferroni correction. The latency data recorded from the channel with the highest N2 amplitude in the forwards optic flow condition was used in the ANOVA. The channel that was chosen varied across participants and testing sessions, but was always one of the four channels mentioned above, and was the same for the three motion conditions in each infant.

The ANOVA revealed a significant three-way interaction of condition, age and group, $F_{(2, 32)} = 8.13$, $P < 0.005$, indicating that only the full-term infants at 12 months of age decreased their latencies significantly from random visual motion (mean = 405 ms,

SD=66), to reversed optic flow (mean = 338 ms, SD=39), to forwards optic flow (mean = 277 ms, SD=49) with approximately 60 ms between each condition (see Figure 5). The preterm babies, on the other hand, did not differentiate between the three visual motion conditions, neither at 5 nor at 12 months. Additionally, a significant two-way interaction of age and group was found, $F(1, 16) = 27.75$, $P < 0.005$, indicating that irrespective of visual motion condition and only at 5 months of age, preterm infants had significantly shorter latencies of approximately 100 ms than full-term infants, and that only the full-term infants reduced their latencies with age, especially for the two optic flow conditions (see Figure 5). The mean latency value of 5-month-old full-term infants for forwards optic flow was 426 ms (SD=70), and when they grew up to 12 months of age the mean latency value decreased with about 150 ms to 277 ms (SD=49). The mean latency decrease from 5 to 12 months for the random visual motion condition, however, was only around 45 ms for the full-term infants.

Figure 5. Means (and SDs) of peak latencies for the two participant groups at both 5 and 12 months obtained from the channels with highest forwards optic flow amplitude in each infant. Mean latency decrease from random visual motion, to reversed optic flow, to forwards optic flow was significant only in full-term infants at 12 months. Also, at 5 months preterm infants had significantly shorter latencies than full-term infants. And finally, the latencies decreased significantly with age for the full-term infants only, especially for the two optic flow conditions.

3.1.2 Amplitude analysis of VEPs

The same ANOVA factor design and electrode selection method were used for the amplitude analysis. The results yielded a significant two-way interaction between age and group, $F(1, 16) = 11.23$, $P < 0.005$, indicating that only at 5 months of age, preterm infants showed significantly lower amplitudes than full-term infants although this difference was not so clear for forwards optic flow, and also that only full-term infants showed decreasing amplitudes when they were 12 months compared to 5 months by approximately -2.5 µV, most notably for reversed optic flow and random visual motion (see Figure 6).
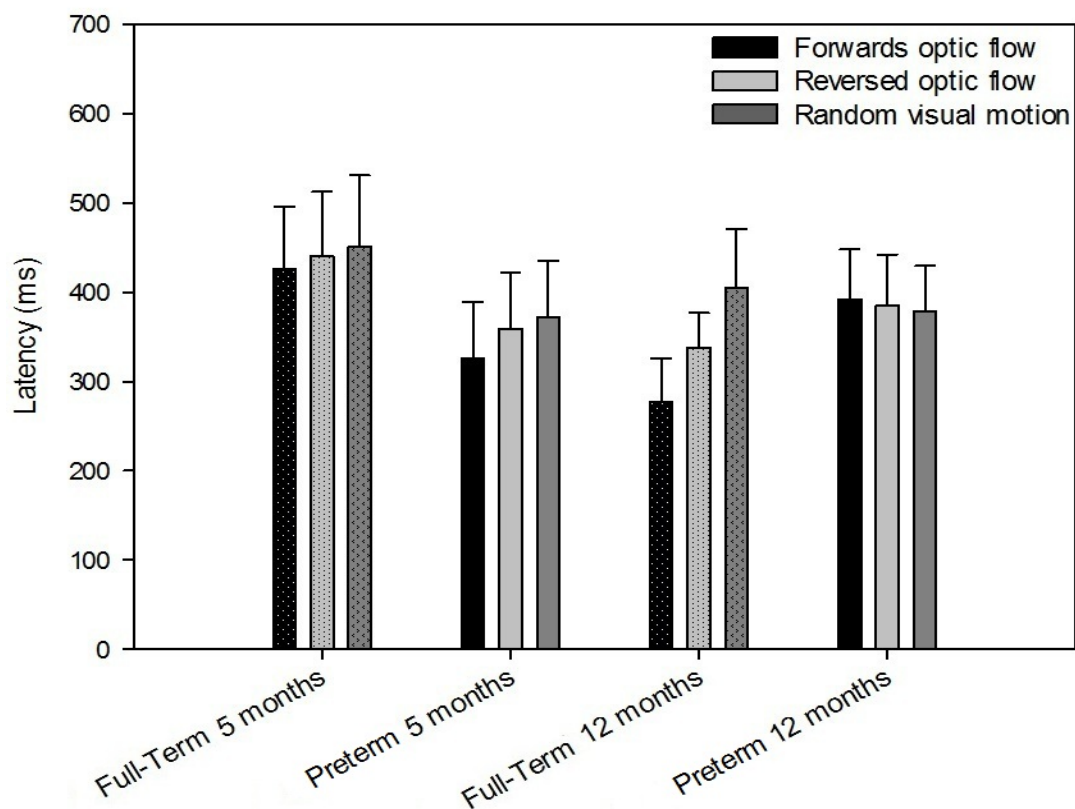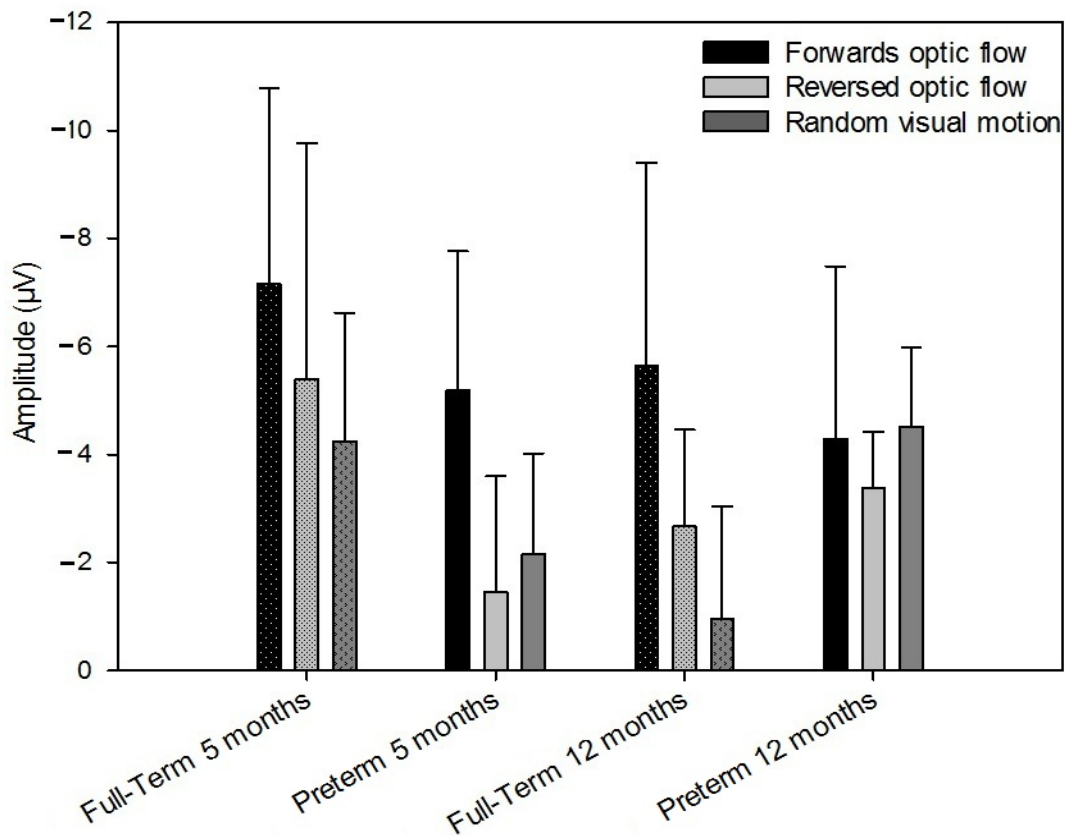

Figure 6. Means (and SDs) of peak amplitudes for the two participant groups at both 5 and 12 months obtained from the channels with highest forwards optic flow amplitude in each infant. At 5 months preterm infants showed significantly smaller amplitudes than full-term infants. Also, amplitudes decreased significantly with age for full-term infants only.

3.1.3 Individual analysis

Following the result that preterm infants did not significantly decrease their latencies with age, the latency data were further explored to see whether there could be a criterion to distinguish the preterm infants who were remarkably delayed in their responses, thus struggling to perceive visual motion efficiently. Field (2005) formulated an outlier as values larger or smaller than mean ± SD*2.5. Due to the fact that preterm infants at 5 months of age were found to have significantly shorter latencies than full-term infants, only criterion values for the 12-month-old full-term infants' latencies were computed based on the mean and standard deviation values for the three visual motion conditions, and the 12-month-old preterm infants who showed latencies above these criterion values were marked (Table 1). The application of the criterion pointed to two preterm infants, namely PW and WK, who at 12 months of age showed extremely long latencies for both forwards and reversed optic flow. In addition, two infants (DO and VR) showed outlier values only for forwards optic flow. However, none of these four preterm infants showed delayed motor development or were bottom shufflers at the time of the second testing.

Full-term	Forwards	Reversed	Random	Preterm	Forwards	Reversed	Random
BT	354	368	456	DO	472	406	380
CY	214	344	288	GG	316	390	330
FU	244	382	510	GQ	400	408	452
HI	322	344	438	HV	298	284	328
KO	284	350	380	IL	376	422	310
NP	202	382	350	PW	422	454	450
TQ	286	308	436	VR	422	336	376
TW	286	276	368	WK	434	440	406
YE	298	290	420	ZL	392	330	374
Mean	277	338	405		392	385	378
SD	49	39	66		56	57	51
Mean+ SD*2.5	*400*	*435*	*570*				

Table 1. VEP latencies (ms) to the three visual motion conditions for both infant groups at 12 months of age. The underlined numbers indicate the preterm infants who showed values greater than mean + SD*2.5 of VEP latency values of the full-term group. Preterm infants PW and WK stood out with their extremely long latencies for both optic flow conditions.

4.0 DISCUSSION

This longitudinal study investigated the developmental manifestations of visual motion perception in the brain during early infancy and whether there are any differences between normally developing full-term and preterm infants. High-density EEG was used to observe cortical electrical activities that emerge as perceptual response mechanisms to structured radial optic flows, i.e., forwards and reversed, and random visual motion. The first testing session was carried out when infants were 5 months old and at the second session infants were 12 months old. Motion specific N2 components of the VEPs of the two groups at the two ages were compared separately for latencies and amplitudes of the waveforms.

In the course of development from 5 months to 12 months a significant improvement in latencies was observed only in full-term infants. They became more sensitive to forwards and reversed optic flow by revealing shorter latencies. This result supports earlier findings of a longitudinal study which compared full-term infants at 3-4 and 11-12 months with the same experimental paradigm (Agyei, Holth, van der Weel & van der Meer, 2012). One contributing factor to the observed acceleration in visual motion perception is possibly neural maturation that provided a basis for more efficient processing of the visual motion scene. It has been shown that not the fibre density but the fibre volume of white matter aggrandizes due to ongoing axonal myelination during early maturational stages until adulthood (Paus, Collins, Evans, Leonard, Pike, et al., 2001; Jito, Nakasu, Ito, Fukami, Morikawa, et al., 2008). Myelin sheaths over the axons serve to increase the speed of electrical impulse propagation from soma to dendrites of the neurons, thus myelination may account for shorter latencies at 12 months. However, full-term infants' N2 latencies to random visual motion did not become saliently shorter with age. This could be associated with the importance of structured information to rely on while moving efficiently. This is in line with findings that infants' postural control depends on and is influenced by structured information more strongly than that of adults (Lee & Aronson, 1974), and that infants show longer latencies than adults when detecting visual motion, especially random motion (van der Meer, et al., 2008). Thus, as infants acquire independent locomotion, they appear to rely more on the structured radial flow around them, and they seem impeded by the lack of structure in random visual motion as evidenced by longer latencies. Therefore, it could be argued that lack of structured information in a visual scene is hindering visual motion perception in infants who recently acquired independent locomotion.

Full-term infants at 12 months showed latencies that were significantly decreasing from random visual motion, to reversed optic flow, to forwards optic flow. Their shortest latency to forwards optic flow and longest latency to random visual motion can be interpreted to mean that they have become sensitive towards structured radial motion, which makes it easier for them to detect structured optic flows as opposed to random visual motion. Similar findings have been reported for 8-month-old full-term infants (van der Meer, et al., 2008), and for 11/12-month-old full-term infants (Agyei, et al., 2012). In neurological studies, it has been found that during the first two postnatal years maturation of the subcortical projection and association pathways was later than maturation of some other white matter tracts of the brain (Kinney, Brody, Kloman, Gilles, 1988). Klaver and his colleagues reviewed studies on neurodevelopment of the visual system and they reported that the number of dendrites and synaptic connections in the primary visual cortex (grey matter) increases during the first months of life and reaches a peak level between the ages of 8 months and 2 years. Additionally, they showed that metabolic activity rate in occipital, parietal, and temporal cortices increases strongly after 3 months whereas in visual association cortex and frontal cortex the rate increase was found only after 6-8 months of age (Klaver, Marcar & Martin, 2011). These increases in the number of dendrites and synaptic connections, and metabolic activity rate could mean that neural functional specialization becomes operational around 8 months of age. Latencies differentiating between the three motion conditions in full-term infants at 12 months but not at 5 months are associated with the neural functional specialization in the dorsal visual stream.

The biased sensitivity towards forwards and reversed optic flows could also be attributed to the necessity and frequent use of structured information to be able to move around efficiently (Lamontagne, et al., 2007; Bruggeman & Warren, 2010). Infants start to explore the environment soon after they are born either in a stroller or on the arms of their parents. Passive experience reveals a minimum level of improvement in sensitivity to optic flow between 3 and 6 months (Gilmore, et al., 2004). For instance, 4-month-old infants are very poor at discriminating different directions simulated by optic flow patterns (Gilmore & Rettke, 2003). However, self-produced locomotion is found to be superior to passive observation and turns out to be crucial for the normal development of visual perception (Held & Hein, 1963), and this is particularly apparent when infants start crawling around the age of 8 months and when they achieve independent walking at around 12 months. It has also been shown that there is a strong coupling between visual motion perception and

postural control, as infants with crawling experience turn out to be more sensitive to optic flow stimuli (Anderson, Campos, Anderson, Thomas, Witherington, et al., 2001) and self-produced locomotion experience leads infants to make better use of the information embedded in optic flow for postural control (Higgins, Campos & Kermoian, 1996). Infants perceiving optic flow in the anterior-posterior direction in a 'moving room' substantially improved their postural responses especially when they learned to sit. However, this improvement was followed by a gradual drop after 9 months although locomotor experience continued (Bertenthal, Rose & Bai, 1997). In the present study, full-term infants had had approximately 3 months crawling experience at the second testing session, and they were in a period in which neural development is very rapid. Hence, the suggestion that functional perception of structured radial flow develops hand in hand with acquired independent locomotion (van der Meer, et al., 2008) is supported.

Surprisingly, the results further indicated that preterm infants neither showed shorter latencies between 5 and 12 months, nor any significant latency differences between the three motion conditions. Even though most of the preterm infants also had had three months of crawling experience at the time of the second testing session, they did not differentiate between the three motion conditions like their full-term peers did. This finding supports the notion of dorsal visual stream impairment caused by premature birth. It has been shown that preterm infants at corrected age of 2-3 months are delayed with several weeks in differentiating change of direction in the horizontal axis compared to full-term infants (Birtles, Braddick, Wattam-Bell, Wilkinson & Atkinson, 2007). Consistently, neuroimaging studies agreed upon that there is white matter abnormality characterised with appearance of diffuse and excessive high signal intensity (DEHSI) throughout the cerebral cortex in preterm infants at the corrected age of birth (Maalouf, Duggan, Rutherford, Counsell, Fletcher, et al., 1999; Counsell, Allsop, Harrison, Larkman, Kennea, et al., 2003; Counsell, Shen, Boardman, Larkman, Kapellou, et al., 2006; Atkinson, et al., 2008; Skiold, Horsch, Hallberg, Engstrom, Nagy, et al., 2010). Controversially, there are promising follow-up studies examining neuro-developmental outcome of the white matter abnormality in 18- and 30-month-old preterm infants showing that there was no association between DEHSI and possible brain damage (Hart, Whitby, Wilkinson, Alladi, Paley, et al., 2011; Skiold, Vollmer, Bohm, Hallberg, Horsch, et al., 2012), as well as follow-up studies showing that DEHSI should be considered a form of white matter injury rather than white matter immaturity (Domizio, Barbante, Puqlieli, Clementini, Domizio, et al., 2005). It could be white matter abnormality that underlies the impairment of the dorsal visual stream

as well as the axonal electrical impulse speed resulting in unimproved latencies at 12 months in preterm infants, or it could just be a normal delay related to premature birth to be recovered at a later age.

It would be interesting with a follow-up study to monitor the developmental progress of the preterm group. Interestingly, when compared to full-term infants, preterm infants at 5 months of age showed significantly shorter latencies regardless of visual motion condition. The fact that preterm infants were tested corrected for prematurity could have caused this faster perceptual response, considering preterm infants' longer exposure to real-world visual flow experiences. If this effect was caused by experience with visual stimuli per se, one would expect full-term infants at the age of 7 months to show equally short latencies as preterm infants at the corrected age of 5 months, corresponding well with the latencies of around 200 ms to forwards optic flow observed in 8-month-old full-term infants (van der Meer, et al., 2008).

Comparison of the amplitudes of the N2 components of the VEPs revealed lower activation values in 5-month-old preterm infants than in full-terms. Amplitudes of brain electrical waveforms represent the synchronous activity of excited neurons (Pfurtscheller & Lopes da Silva, 1999), so it can be argued that higher amplitudes mean more synchronous signals elicited by activated neurons in larger areas. Hence, the smaller amplitudes of 5-month-old preterm infants could be interpreted as a lower number of synchronized neurons which could imply less adapted and specialized neural behaviour for perception of visual motion (Huttenlocher & Dabholkar, 1997). The lower activation values that were found in 12-month-old full-term infants compared to when they were 5 months old are most likely associated with bone growth. Thicker skulls at 12 months have probably caused this result, leading to more impedance while measuring the cortical electrical activity (Grieve, Emerson, Fifer, Isler & Stark, 2003).

An additional observation of the four posterior electrode channels which showed the highest N2 amplitude values in the forwards optic flow condition of the grand average VEPs (Figure 3) suggested that there is right hemisphere lateralization of visual motion perception when considering 12-month-old full-term infants' dominant electrode location. It has been shown by both lesion and experimental studies that most of the visuo-spatial tasks are dominated by the right hemisphere (Ornstein, Johnstone, Herron & Swencionis,

1980; Kim, Morrow, Passafiume & Boller, 1984; Deutsch, Bourbon, Papanicolaou & Eisenberg, 1988; Jager & Postma, 2003; Vogel, Bowers & Vogel, 2003; Rilea, Roskos-Ewoldsen & Boles, 2004; Iachini, Ruggiero, Conson & Trojano, 2008; Loenneker, Klaver, Bucher, Lichtensteiger, Imfeld, et al., 2010). In the study that showed shorter latencies to structured forwards optic flow than random visual motion in adults on the same task, channels with the highest N2 amplitude values in the forwards optic flow condition of the grand average VEPs were localized in the right hemisphere as well (van der Meer, et al., 2008). The right hemispheric lateralization at 12 months in full-term infants could be the sign of a fine developmental progress on the way to acquire mature visual motion perception, whereas the fact that the preterm group at 12 months did not show any signs of right hemisphere lateralization could be indicative of inadequate developmental progress.

When exploring the developmental characteristics of visual motion perception and the effects of prematurity thereon, an outlier criterion was suggested for the purpose of identifying extremely late responders among the preterm infants at 12 months who might be at risk of developmental disorders. Although two preterm infants stood out, their longer latencies could represent a normal developmental delay to be recovered as they grow older. To be able to utilize the criterion as an early screening tool for visual motion perception impairment, more longitudinal follow-up on these preterm infants is necessary. In another study, longitudinal looming data were collected on the same group of preterm babies and it would be interesting to see whether the same preterm babies that did poorly in the present optic flow study, also had problems with identifying and timing the looms.

In conclusion, the present study found that full-term infants follow a developmental path where they increase their sensitivities to optic flow, and also become capable of detecting structured optic flow more efficiently than random visual motion with age. These improvements in full-term infants have been attributed to neural maturation accompanied by locomotor experiences. Preterm infants, on the other hand, followed a different developmental path where they did not increase their sensitivities to optic flow, nor did they become capable of detecting structured optic flow more efficiently than random visual motion with age. This difference in functional visual motion perception in preterm infants could be attributed to a white matter abnormality related to visual dorsal stream vulnerability. More longitudinal research should be carried out to gain a better

understanding of the developmental progress of visual motion perception in full-term and preterm infants before the results can be used to aid an early diagnosis.

REFERENCES

Aarnoudse-Moens, C. S. H., Weisglas-Kuperus, N., van Goudoever, J. B., & Oosterlaan, J. (2009). Meta-analysis of neurobehavioral outcomes in very preterm and/or very low birth weight children. *Pediatrics, 124*(2), 717-728.

Agyei, S. B., Holth, M., van der Weel, F. R., & van der Meer, A. L. (2012). Longitudinal study of perception of structured optic flow and random visual motion in infants using high-density EEG. Under review for *Developmental Neuroscience.*

Anderson, D. I., Campos, J. J., Anderson, D. E., Thomas, T. D., Witherington, D. C., Uchiyama, I., & Barbu-Roth, M. A. (2001). The flip side of perception-action coupling: locomotor experience and the ontogeny of visual-postural coupling. *Human Movement Science,* 20, 461-487.

Atkinson, J., Birtles, D., Anker, S., Braddick, O., Rutherford, M., Cowan, F., & Edwards, D. (2008a). High-density VEP measures of global form and motion processing in infants born very preterm. *Journal of Vision, 8*(6), 422-422a.

Atkinson, J., & Braddick, O. (2007). Visual and visuocognitive development in children born very prematurely. *Progress in Brain Research,* 164, 123-149.

Atkinson, J., Hood, B., Wattam-Bell, J., & Braddick, O. (1992). Changes in infants' ability to switch visual attention in the first three months of life. *Perception,* 21, 643-653.

Atkinson, J., Braddick, O., Anker, S., Nardini, M., Birtles, D., Rutherford, M. A., Mercuri, E., Dyet, L. E., Edwards, A. D., & Cowan, F. M. (2008b). Cortical vision, MRI, and developmental outcome in preterm infants. *Archives of Diseases in Childhood – Fetal and Neonatal,* 93, F292-F297.

Braddick O. J. (1993). Orientation- and motion-selective mechanisms in infants. In: Simons K. (Ed.), Early Visual Development: Normal and abnormal (pp. 163-177). New York: Oxford University Press.

Braddick, O., Atkinson, J., Hood, B., Harkness, W., Jackson, G., & Vargha-Khademt, F. (1992). Possible blindsight in infants lacking one cerebral hemisphere. *Nature,* 360, 461-463.

Braddick, O., Birtles, D., Wattam-Bell, J., & Attkinson, J. (2005). Motion- and orientation-specific cortical responses in infancy. *Vision Research,* 45, 3169-3179.

Braddick O. J., Wattam-Bell, J., & Atkinson, J. (1986). Orientation-specific cortical responses develop in early infancy. *Nature*, 320, 617-619.

Beets, I. A. M., Rösler, F., & Fiehler, K. (2010). Non-visual motor learning improves visual motion perception: evidence from violating the two-thirds power law. *Journal of Neurophysiology,* 104, 1612-1624.

Berg, P., & Scherg, M. (1994). A multiple source approach to the correction of eye artefacts. *Electroencephalography and Clinical Neurophysiology, 90*(3), 229-241.

Bertenthal, B. I., Rose, J. L., & Bai, D. L. (1997). Perception-action coupling in the development of visual control of posture. *Journal of Experimental Psychology: human Perception and Performance, 23*(6), 1631-1643.

Bhutta, A. T., Cleves, M. A., Casey, P. H., Cradock, M. M., & Anand, K. J. S. (2002). Cognitive and behavioural outcomes of school-aged children who were born preterm: a meta-analysis. *The Journal of American Medical Association, 288*(6), 728-737.

Birtles, D. B., Braddick, O. J., Wattam-Bell, J., Wilkinson, & A. Atkinson, J. (2007). Orientation and motion-specific visual cortex responses in infants born preterm. *NeuroReport, 18*(18), 1975-1979.

Bruggeman, H., Zosh, W., & Warren, W. H. (2007). Optic flow drives human visual-locomotor adaptation. *Current Biology, 17*(23), 2035-2040.

Bruggeman, H., & Warren, W. H. (2010). The direction of walking – but not throwing or kicking – is adapted by optic flow. *Psychological Science, 21*(7), 1006-1013.

Budai, R., Contento, G., Locatelli, T., & Comi, G. (1995). Non-invasive multielectrode array for high resolution sampling of scalp-recorded potential fields. *Journal of Medical Engineering and Technology, 19*(2-3), 52-56.

Counsel, S. J., Allsop, J. M., Harrison, M. C., Larkman, D. J., Kennea, N. L., Kapellou, O., Cowan, F. M., Hajnal, J. V., Edwards, A. D., & Rutherford, M. A. (2003). Diffusion-weighted imaging of the brain in preterm infants with focal and diffuse white matter abnormality. *Pediatrics, 112*(1), 1-7.

Counsell, S. J., & Boardman, J. P. (2005). Differential brain growth in the infant born preterm: current knowledge and future developments from brain imaging. *Seminars in Fetal & Neonatal Medicine, 10,* 403-410.

Counsell, S. J., Shen, Y., Boardman, J. P., Larkman, D. J., Kapellou, O., Ward, P., Allsop, J. M., Cowan, F. M., Hajnal, J. V., Edwards, D., & Rutherford, M. A. (2006). Axial and radial diffusivity in preterm infants who have diffuse white matter changes on magnetic resonance imaging at term-equivalent age. *Pediatrics, 117*(2), 376-386.

Creem, S. H., & Proffitt, D. R. (2001). Defining the cortical visual systems: "What," "where," and "how." *Acta Psychologica, 107,* 43-68.

Delobel-Ayoub, M., Arnaud, C., White-Koning, M., Casper, C., Pierrat, V., Garel, M., Burguet, A., Roze, J., Matis, J., Picaud, J., Kaminski, M., & Larroque, B. (2009). Behavioural problems and cognitive performance at 5 years of age after very preterm birth: the EPIPAGE study. *Pediatrics, 123*(6), 1485-1492.

Deutsch, G., Bourbon, W. T., Papanicolaou, A. C., & Eisenberg, H. M. (1988). Visuo-spatial tasks compared via activation of regional cerebral blood flow. *Neuropsychologia, 26*(3), 445-452.

de Jong, M., Verhoeven, M., & van Baar, A. L. (2012). School outcome, cognitive functioning, and behaviour problems in moderate and late preterm children and adults: a review. *Seminars in Fetal & Neonatal Medicine, 17,* 163-169.

Domizio, S., Barbante, E., Puqlielli, C., Clementini, E., Domizio, R., Sabatino, G. M., Albanese, A., Colosimo, C., & Sabatino, G. (2005). Excessively high magnetic resonance signal in preterm infants and neuropsychobehavioural follow-up at 2 years. *International Journal of Immunopathology and Pharmacology, 18*(2), 365-375.

Downie, A. L. S., Jacobson, L. S., Frisk, V., & Ushycky, I. (2003). Periventricular brain injury, visual motion processing, and reading and spelling abilities in children who were extremely low birth weight. *Journal of the International Neuropsychological Society, 9,* 440-449.

Ferree, T. C., Luu, P., Russell, G. S., & Tucker, D. M. (2001). Scalp electrode impedance, infection risk, and EEG data quality. *Clinical Neurophysiology, 112,* 536-544.

Field, A. (2005). Discovering statistics using SPSS (Second ed. Vol.2): SAGE Publications Ltd, London.

Fielder, A. R., Harper, M. W., Higgins, J. E., Clarke, C. M., & Corrigan, D. (1983). The reliability of the VEP in infancy. *Ophthalmic Pediatrics and Genetics, 3*(2), 73-82.

Fujioka, T., Mourad, N., He, C., & Trainor, L. J. (2011). Comparison of artefact correction methods for infant EEG applied to extraction of event-related potential signals. *Clinical Neurophysiology, 122*(1), 43-51.

Gibson, J. J. (1979). *The Ecological Approach to Visual Perception*. New Jersey: Lawrence Erlbaum Associates, Inc.

Gilmore, R. O., & Rettke, H. J. (2003). Four-month-olds' discrimination of optic flow patterns depicting different directions of observer motion. *Infancy, 4*(2), 177-200.

Gilmore, R. O., Baker, T. J., & Grobman, H. K. (2004). Stability in young infants' discrimination of optic flow. *Developmental Psychology, 40*(2), 259-270.

Gilmore, R. O., Hou, C., Pettet, M. W., & Norcia, A. M. (2007). Development of cortical responses to optic flow. *Visual Neuroscience, 24*, 845-856.

Greenlee, M., W. (2000). Human cortical areas underlying the perception of optic flow: Brain imaging studies. *International Review of Neurobiology, 44*, 269-292.

Grieve, P. G., Emerson, R. G., Fifer, W. P., Isler, J. R., & Stark, R. I. (2003). Spatial correlation of the infant and adult electroencephalogram. *Clinical Neurophysiology, 114*, 1594-1608.

Guzzetta, A., Tinelli, F., Del Viva, M. M., Bancale, A., Arrighi, R., Pascale, R. R., & Cioni, G. (2009). Motion perception in preterm children: role of prematurity and brain damage. *NeuroReport, 20*(15), 1339-1341.

Hart, A., Whitby, E., Wilkinson, S., Alladi, S., Paley, M., & Smith, M. (2011). Neuro-developmental outcome at 18 months in premature infants with diffuse excessive high signal intensity on MR imaging of the brain. *Pediatric Radiology, 41*, 1284-1292.

Held, R., & Hein, A. (1963). Movement-produced stimulation in the development of visually guided behaviour. *Journal of Comparative and Physiological Psychology, 56*(5), 872-876.

Higgins, C. I., Campos, J. J., & Kermoian, R. (1996). Effect of self-produced locomotion on infant postural compensation to optic flow. *Developmental Psychology, 32*(5), 836-841.

Hou, C., Gilmore, R. O., Pettet, M. W., & Norcia, A. M. (2009). Spatio-temporal tuning of coherent motion evoked responses in 4–6 month old infants and adults. *Vision Research,* 49, 2509-2517.

Huttenlocher, P. R., & Dabholkar, A. S. (1997). Regional differences in synaptogenesis in human cerebral cortex. *The Journal of Comparative Neurology,* 387, 167-178.

Iachini, T., Ruggiero, G., Conson, M., & Trojano, L. (2009). Lateralization of egocentric and allocentric spatial processing after parietal brain lesion. *Brain and Cognition,* 69, 514-520.

Ille, N., Berg, P., & Scherg, M. (2002). Artifact correction of the ongoing EEG using spatial filters based on artifact and brain signal topographies. *Journal of Clinical Neurophysiology, 19*(2), 113-124.

Itoh, K., Fujii, Y., Kwee, I. L., & Nakada, T. (2005). MT+/V5 activation without conscious motion perception: a high-field fMRI study. *Magnetic Resonance in Medical Science, 4*(2), 69-74.

Jacobson, L. S., Frisk, V., & Downie, A. L. S. (2006). Motion defined form processing in extremely premature children. *Neuropsychologia,* 44, 1777-1786.

Jager, G., & Postma, A. (2003). On the hemispheric specialization for categorical and coordinate spatial relations: a review of the current evidence. *Neuropsychologia,* 41, 504-515.

Jito, J., Nakasu, S., Ito, R., Fukami, T., Morikawa, S., & Inubushi, T. (2008). Maturational changes in diffusion anisotropy in the rat corpus callosum: comparison with quantitative histological evaluation. *Journal of Magnetic Resonance Imaging,* 28, 847-854.

Johnson, S. (2007). Cognitive and behavioural outcomes following very preterm birth. *Seminars in Fetal & Neonatal Medicine,* 12, 363-373.

Jouen, F., Lepecq, J-C., Gapenne, O., & Bertenthal, B. I. (2000). Optic flow sensitivity in neonates. *Infant Behaviour & Development,* 23, 271-284.

Kaufmann, F. (1995). Development of motion perception in early infancy. *European Journal of Paediatrics, 154*(3), S48-S53.

Kayed, N. S., & van der Meer, A. L. (2009). A longitudinal study of prospective control in catching by full-term and preterm infants. *Experimental Brain Research, 194*(2), 245-258.

Kim, Y., Morrow, L., Passafiume, D., & Boller, F. (1984). Visuoperceptual and visuomotor abilities and locus of lesion. *Neuropsychologia, 22*(2), 177-185.

Kinney, H. C., Brody, B. A., Kloman, A. S., & Gilles, F. H. (1988). Sequence of central nervous system myelination in human infancy. II. Patterns of myelination in autopsied infants. *Journal of Neuropathology and Experimental Neurology, 47*(3), 217-234.

Klaver, P., Marcar, V., & Martin, E. (2011). Neurodevelopment of the visual system in typically developing children. *Progress in Brain Research,* 189, 113-136.

Kobayashi, Y., Yoshino, A., Kawamoto, M., Takahashi, Y., & Nomura, S. (2004). Perception of apparent motion on depth: a high-density electrical mapping study in humans. *Neuroscience Letters,* 354, 115-118.

Lamontagne, A., Fung, J., McFadyen, B. J., & Faubert, J. (2007). Modulation of walking speed by changing optic flow in persons with stroke. *Journal of Neuroengineering and Rehabilitation, 4*(22).

Lappe, M., Bremmer, F., & van der Berg, A. V. (1999). Perception of self-motion from visual flow.*Trends in Cognitive Sciences, 3*(9), 329-336.

Lee, D. N., & Aronson, E. (1974). Visual proprioceptive control of standing in human infants. *Perception & Psychophysics, 15*(3), 529-532.

Lindsen, J. P., & Bhattacharya, J. (2010). Correction of blink artefacts using independent component analysis and empirical mode decomposition. *Psychophysiology, 47*(5), 955-960.

Loenneker, T., Klaver, P., Bucher, K., Lichtensteiger, J., Imfeld, A., & Martin, E. (2010). Microstructural development: organizational differences of the fiber architecture between children and adults in dorsal and ventral visual streams. *Human Brain Mapping, 32*(6), 935-946.

Maalouf, E. F., Duggan, P. J., Rutherford, M. A., Counsell, S. J., Fletcher, A. M., Battin, M., Cowan, F., & Edwards, A. D. (1999). Magnetic resonance imaging of the brain in a cohort of extremely preterm infants. *The Journal of Pediatrics, 135*(3), 351-357.

MacKay, T. L., Jacobson, L. S., Ellemberg, D., Lewis, T. L., Maurer, D., & Casiro, O. (2005). Deficits in the processing of local and global motion in very low birth weight children. *Neuropsychologia, 43,* 1738-1748.

Martin, J. A., Hamilton, B. E., Sutton, P. D., Ventura, S. J., Menacker, F., & Munson, M. L. (2003). Births: Final data for 2002. *National Vital Statistic Reports, 52*(10), 1-116.

Newsome, W. T., & Paré, E. B. (1988). A selective impairment of motion perception following lesions of the middle temporal visual area (MT). *The Journal of Neuroscience, 8*(6), 2201-2211.

Ornstein, R., Johnstone, J., Herron, J., & Swencionis, C. (1980). Differential right hemisphere engagement in visuospatial tasks. *Neuropsychologia, 18,* 49-64.

Paus, T., Collins, D. L., Evans, A. C., Leonard, G., Pike, B., & Zijdenbos, A. (2001). Maturation of white matter in the human brain: a review of magnetic resonance studies. *Brain Research Bulletin, 54*(3), 255-266.

Pfurtscheller, G., & da Silva, F. H. L. (1999). Event-related EEG/MEG synchronization and desynchronization: basic principles. *Clinical Neurophysiology, 110,* 1842-1857.

Pham, T. T., Croft, R. J., Cadusch, P. J., & Barry, R. J. (2011). A test of four EOG correction methods using an improved validation technique. *International Journal of Psychophysiology, 79*(2), 203-210.

Picton, T. W., Bentin, S., Berg, P., Donchin, E., Hillyard, S. A., Johnson, R., Miller, G. A., Ritter, W., Ruchkin, D. S., Rugg, M. D., & Taylor, M. J. (2000). Guidelines for using human event-related potentials to study cognition: recording standards and publication criteria. *Psychophysiology, 37,* 127-152.

Riecansky, I. (2004). Extrastriate area V5 (MT) and its role in the processing of visual motion. *Ceskoslovenska Fysiologie, 53*(1), 17-22.

Rilea, S. L., Roskos-Ewoldsen, B., & Boles, D. (2004). Sex differences in spatial ability: A lateralization of function approach. *Brain and Cognition, 56,* 332-343.

Rosander, K., Nystrom, P., Gredeback, G., & von Hofsten C. (2007). Cortical processing of visual motion in young infants. *Vision Research, 47,* 1614-1623.

Salt, A., & Redshaw, M. (2005). Neurodevelopmental follow-up after preterm birth: follow up after two years. *Early Human Development, 82,* 185-197.

Shao, S. Y., Shen, K. Q., Ong, C. J., Wilder-Smith, E. P., & Li, X. P. (2009). Automatic EEG artefact removal: A weighted support vector machine approach with error correction. *IEEE Transactions on Biomedical Engineering, 56*(2), 336-344.

Shirai, N., & Yamaguchi, M. K. (2010). How do infants utilize radial optic flow for their motor actions?: A review of behavioural and neural studies. *Japanese Psychological Research, 52*(2), 78-90.

Skiold, B., Horsch, S., Hallberg, B., Engstrom, M., Nagy, Z., Mosskin, M., Blennow, M., & Aden, U. (2010). White matter changes in extremely preterm infants, a population-based diffusion tensor imaging study. *Acta Pediatrica, 99,* 842-849.

Skiold, B., Vollmer, B., Bohm, B., Hallberg, B., Horsch, S., Mosskin, M., Lagercrantz, H., Aden, U., & Blennow, M. (2012). Neonatal magnetic resonance imaging and outcome at age 30 months in extremely preterm infants. *The Journal of Pediatrics, 160*(4), 559-566.

Smith, A. T., Wall, M. B., Williams, A. L., & Singh, K. D. (2006). Sensitivity to optic flow in human visual areas MT and MST. *European Journal of Neuroscience, 23,* 561-569.

Taylor, N. M., Jacobson, L. S., Maurer, D., & Lewis, T. L. (2009). Differential vulnerability of global motion, global form, and biological motion processing in full-term and preterm children. *Neuropsychologia, 47*, 2766-2778.

Tucker, D. M. (1993). Spatial sampling of head electrical fields: the geodesic sensor net. *Electroencephalography and Clinical Neurophysiology, 87*(3), 154-163.

Turano, K. A., Yu, D., Hao, L., & Hicks, J. C. (2005). Optic-flow and egocentric-direction strategies in walking: Central vs. peripheral visual field. *Vision Research, 45*, 3117-3132.

van Braeckel, K., Butcher, P. R., Geuze, R. H., van Duijn, M. A., Bos, A. F., & Bouma, A. (2010). Difference rather than delay in development of elementary visuomotor processes in children born preterm without cerebral palsy: a quasi-longitudinal study. *Neuropsychology, 24*(1), 90-100.

van den Boomen, C., van der Smagt, M. J., & Kemner, C. (2012). Keep your eyes on development: the behavioural and neurophysiological development of visual mechanisms underlying form processing. *Frontiers in Psychiatry, 3*(16), 1-20.

van der Meer, A. L., Fallet G., & Van der Weel, F. R. (2008). Perception of structured optic flow and random visual motion in infants and adults: A high-density EEG study. *Experimental Brain Research, 186*, 493-502.

van der Meer, A. L., van der Weel, F. R., & Lee, D. N. (1994). Prospective control in catching by infants. *Perception, 23*(3), 287-302.

Vogel, J. J., Bowers, C. A., & Vogel, D. S. (2003). Cerebral lateralization of spatial abilities: A meta-analysis. *Brain and Cognition, 52*, 197-204.

Wall, M. B., Lingnau, A., Ashida, H., & Smith, A. T. (2008a). Selective visual responses to expansion and rotation in the human MT complex revealed by fMRI adaptation. *European Journal of Neuroscience, 27*, 2747-2757.

Wall, M. B., & Smith, A. T. (2008b). The representation of ego-motion in the human brain. *Current Biology, 18*, 191-194.

Warren, W. H., Kay, Jr., B. A., Zosh, W. D., Duchon, A. P., & Sahuc, S. (2001). Optic flow is used to control human walking. *Nature Neuroscience, 4*(2), 213-216.

Wilkie, R. M., & Wann, J. P. (2003). Eye-movements aid the control of locomotion. *Journal of Vision,* 3, 677-684.