Development of visual motion processing: Phase and peak latencies of direction-specific visual evoked potential

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The direction-reversal visual evoked potential (DR-VEP) latency is a key measure of the development of motion processing in infancy. However, the latency of this response has not been previously investigated. For other stimuli, both the latency of an initial peak and a latency measure calculated from steady-state phase as a function of frequency have been shown to be important and distinctive indicators of development. The latter measure is hypothesized to reflect the time course of cortical processing beyond the initial response that generates the first positive peak. DR-VEP was tested in 61 adults at 1–16 reversals per second (r/s) and 76 infants (age 7.7–79.0 weeks) at 2–8 r/s. In addition to measuring the transient peak latency at 1–3 r/s, latencies from the gradient of phase against reversal rates were also calculated from steady-state recordings at 1–16 r/s. For both adults and infants, peak latencies were similar for 1–3 r/s, while the calculated latency was substantially longer. Thirty-nine percent of adults and 17% of infants showed additional early transient peaks. We suggest that this early peak may reflect activation of extrastriate areas by motion, by a route that bypasses V1. While both transient latencies were similar to adult values around the onset of DR responses at 10 weeks of age, the latency calculated from phase values did not asymptote to the adult value of 207 ms until around 30 weeks. The overall time course of the response to direction reversal is prolonged compared with the transmission delay that generates the initial transient peak, presumably reflecting feed-forward, lateral, and recurrent connections that refine and elaborate the directional response of cortical neurons. While the peak latencies stay relatively unchanged throughout development, the dynamics of further motion processing are not mature until after 8 months of age. These measures may prove important indicators of motion development in future clinical evaluations.

Introduction

Directional selectivity is a key aspect of cortical visual processing, underlying many perceptual capabilities, including registering object motion and self motion, segmentation, space perception from motion parallax, and detection of biological motion. Such directional selectivity is found in a population of neurons in areas V1 and V2, which provide input to extrastriate areas, notably V5 (MT), which are known to subserve aspects of motion perception. Behavioral and evoked-potential studies (reviewed by Braddick, Atkinson, & Wattam-Bell, 2003) have indicated that this selectivity is not present in human infants in the first weeks of life but develops postnatally. Wattam-
Bell (1991) found that visual evoked potential (VEP) responses to direction reversal (DR-VEP) were typically first recorded at around 10 weeks of age, although this was a function of stimulus velocity, with responses to motion at 20 deg/s emerging several weeks later than for 5 deg/s. Behavioral studies yielded evidence of directional motion discrimination earlier, around 7 weeks (Wattam-Bell, 1992, 1994, 1996; Braddick et al., 2003), but the optokinetic responses to movement that are present at birth appear to reflect a different, subcortical mechanism (Mason, Braddick, & Wattam-Bell, 2003). Other VEP methods that provide evidence of directional sensitivity concur that cortical responses to motion direction cannot be detected before approximately 6–7 weeks of age (Birch, Fawcett, & Stager, 2000). However, the way that directional responses develop after their initial emergence has been less extensively studied.

In this paper we report VEP experiments designed to throw light on the maturation of the cortical mechanisms of developmental selectivity in infancy. Studies have shown that latency measures of VEP are better indicators of visual development than amplitude both within and between subjects (Strasburger, Scheidler, & Rentschler, 1988; Tomoda, Tobimatsu, & Mitsudome, 1999; Sarnthein, Andersson, Zimmermann, & Zumsteg, 2009). We present here evidence on how the maturation of directional processes is reflected in changes of the latency of the DR-VEP.

The latency of infants’ VEP responses to pattern-reversal (PR-VEP) shows a striking development during the first year; the latency of the first positive peak (P1) in the transient VEP reduces from about 250 ms at birth, reaching adult values of 100–110 ms around 15 weeks of age (Sokol & Jones, 1979; Moskowitz & Sokol, 1983; McCulloch, Orbach, & Skarf, 1999). This initial peak presumably reflects the transmission time of visual information to the cortex and may also include the timing of some cortical processes involved in initiating the response to contrast. However, it is likely that significant cortical processing occurs after this initial VEP peak. Lee, Birtles, Wattam-Bell, Atkinson, and Braddick (2012a) applied a different measure of response timing, designed to tap such later processing, to the development of the pattern reversal response. If the steady-state VEP is measured across a range of temporal frequencies, the phase of the response at the stimulus reversal frequency can be extracted, and the gradient of a plot of this phase against temporal frequency (TF) is a measure of latency (Regan, 1966; Spekreijse et al., 1978). However, this latency reflects the timing of the steady-state response over a whole cycle. If the temporal relation between stimulus and the VEP response is other than just a pure delay and is influenced the temporal frequency response of cortical processes, then the latency calculated from this was a function of stimulus velocity, with responses to motion at 20 deg/s emerging several weeks later than for 5 deg/s. Behavioral studies yielded evidence of directional motion discrimination earlier, around 7 weeks (Wattam-Bell, 1992, 1994, 1996; Braddick et al., 2003), but the optokinetic responses to movement that are present at birth appear to reflect a different, subcortical mechanism (Mason, Braddick, & Wattam-Bell, 2003). Other VEP methods that provide evidence of directional sensitivity concur that cortical responses to motion direction cannot be detected before approximately 6–7 weeks of age (Birch, Fawcett, & Stager, 2000). However, the way that directional responses develop after their initial emergence has been less extensively studied.

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Using these two measures, Lee et al. (2012a) confirmed earlier findings on the maturation of the transient P1, but found that the latency calculated from the phase versus TF function was initially higher than the P1 latency, showed a more protracted development, and did not asymptote to adult values until 30 weeks of age. In a subsequent paper, Lee, Birtles, Wattam-Bell, Atkinson, and Braddick (2012b) made a similar comparison of the transient P1 and calculated latencies of infants’ VEP responses to a change of stimulus
orientation (OR-VEP) and showed that in this case, the calculated latency remained considerably longer than the P1 latency from early infancy through to adulthood.

These results imply that multiple processes determine the time course of VEP responses during development: an initial delay reflecting transmission time and possibly early cortical processing, and a subsequent time course, which is reflected in the calculated latency but not the P1 latency. This latter time course is more prolonged, and more apparent in adults, for a VEP response reflecting cortical spatial selectivity (the OR-VEP) than for a simple response to a change in contrast (the PR-VEP), presumably reflecting the more elaborate cortical processing involved in the analysis of orientation. We propose that an analogous analysis of responses to direction reversal may indicate the developmental course of the temporally extended processes involved in visual motion processing.

We hypothesize (a) that the latency of the initial transient peak DR-VEP will show a developmental course that includes the changes in transmission time seen also for the PR-VEP, and (b) that the calculated latency will be longer and develop more slowly, reflecting the maturation of the striate and extrastriate cortical networks that compute directional motion over an extended time course.

The DR-VEP, introduced by Wattam-Bell (1991, 1996), uses the stimulus sequence illustrated in Figure 2. A simple reversal of motion direction in a random-pixel pattern is accompanied by local contrast events that could be detected by nondirectional neurons. The reversals are therefore accompanied by replacement of the random pixel pattern (jumps), and to allow the directional component of the VEP response to be isolated, these reversals are embedded in a sequence of jumps without direction reversals. The analysis required to measure the latency of the directional component is explained in the methods section below.

This paper investigates (a) validity and reliability of latency measures for the DR-VEP in tracking motion processing; (b) the relation between transient P1 latency and the phase-based calculated latency in DR-VEP; and (c) the developmental courses of DR latencies as measured with both approaches. Similar to the finding for PR-VEP (Lee et al., 2012a), we expect that we may find a longer phase-based calculated latency compared to the P1 latency for DR-VEP, reflecting the inclusion of additional feedback and internal processing loops compared to the initial directional responses signaled by P1. The comparison of infants and adults is intended to tap into different developmental routes of these components of the motion processing pathway.

**Methods**

**Participants**

Sixty-one adults (median age 21.4 years, range 17–43 years; 38 female, 23 male) with normal or corrected to normal vision and visual acuity (20/20) and 76 healthy full term infants (7.0–79.0 weeks; 36 girls, 40 boys) born within 14 days of their due date were recruited (analysis of variance [ANOVA] revealed no significant effect of pre- or postmaturity in this range affecting latency). This research adhered to the tenets of the Declaration of Helsinki. Informed consent was obtained from adult participants or the parents of infant participants after explaining the nature and possible consequences of the study. This research was approved by Oxford’s Applied and Qualitative Research Ethics Committee.

**Stimulus**

The DR stimulus used in this paper is the same stimulus studied in Wattam-Bell (1991) and Braddick, Birtles, Wattam-Bell, and Atkinson (2005). It consisted of a 0.44 pixel-size random array displaced horizontally at 5.5 deg/sec, with the direction of motion periodically reversed (the DR frequency). The pixel pattern was replaced with a panel of new random pixels in “jumps,” which occurred at a rate twice that of the DR frequency (i.e., the jump occurred every 125 ms for a 4 reversals per second [r/s] DR) (Figure 2).
The pattern was displayed on a computer monitor 40 cm from the participants' eyes. Stimuli were generated using the LUA scripting language (ver. 5.1; www.lua.org), running on a PC (Windows XP; Microsoft, Redmond, WA), and presented on a 17-inch CRT monitor (800 × 600 pixel resolution, viewable area 323 × 240 mm [18.4 deg × 13.7 deg] at the viewing distance of 40 cm) at a 100-Hz frame rate. The display computer was coupled to a recording computer (PC).

**VEP recording**

Three gold cup electrodes were used to record VEP: one on the vertex, one 1 cm above the inion, and a ground electrode positioned high on the forehead. Signals were recorded using a computer-based acquisition system (Espion; Diagnosys, Cambridge, UK). Impedance was measured with an applied voltage at 1000 Hz and electrodes were adjusted until this was <10 kΩ. Signals were amplified (20,000×), band pass filtered between 0.5 and 30 Hz, and sampled at 1000 Hz. Phase response was measured for each temporal frequency to ensure that it was not affected by the band pass filtering. Less than 5° phase shift for all temporal frequencies were found except for 1 r/s (10° phase shift), which had no significant effect on the calculated latency values. In addition, measurement using a photoelectric photometer revealed that there were systematic software delays of 25 ms between the stimulus event at the middle of the computer screen and the recording cycle. Twenty-five milliseconds was thus subtracted from all latency measurements.

One hundred epochs (two cycles per epoch) were averaged on the computer. Any epoch containing signals greater than 200 µV in amplitude was automatically rejected from the signal averaging as artefact. The operator could use the computer mouse button to reject the current epoch if the participant was inattentive. To minimize onset effects, recording began a few seconds after the stimuli appeared. Different temporal frequencies were tested in a randomized fashion to minimize any systematic adaptation effects. Because each recording contained two complete cycles, the total recording epoch was 2 s for 1 r/s, 1 s for 2 r/s, 0.5 s for 4 r/s, etc.

For adults, up to 11 different temporal frequencies of 1, 2, 3, 4, 4.8, 6, 6.86, 8, 9.6, 12, and 16 r/s were used. For infants, up to five different temporal frequencies of 2, 3, 4, 6, and 8 r/s were tested. A small noisy toy was shaken in the center of the computer screen to attract their attention. Recording was interrupted when subjects became inattentive or looked away. Fewer temporal frequencies were used with infants because of their limited attention span and available recording time.

**Transient P1 latency**

In the DR stimulus sequence, each reversal of direction was accompanied by simultaneous replacement of the random pixel pattern (“jump”) (Figure 2). This allowed the use of interleaved jumps to exclude nondirectional effects associated with the reversal. However, this meant that the reversal was accompanied by simultaneous local contrast changes, and these may have contributed to the initial peak response. To “dejump” (i.e., isolate the component of the peak due to direction reversal), the second half of the recorded waveform, which contained the effects of a jump without direction reversal, was subtracted from the first half of the VEP recording for one reversal cycle (reversal + jump) (Figure 3; Braddick et al., 2010). For example, a recording of 2 r/s with two complete reversals would be divided into four chunks: DR response and jump for the first 25 to 256 ms, jump only response for 257–491 ms, DR and jump for 492–726 ms, and finally jump only for 727–961 ms (Figure 3).

For the transient VEP, the timing to produce the highest positive peak values, P1, in this modified waveform was manually selected for the low temporal frequencies (adults, 1, 2, and 3 r/s; infants, 2 and 3 r/s). P1 was manually selected within the time window 80–150 ms in adults and 80–250 ms for infants. The mean latencies across these low temporal frequencies were calculated and used in subsequent analysis, after confirming that there was no significant difference of P1 latency among the different temporal frequencies. Since each recording yielded two complete cycles, an average latency of the two peaks was used for all the subsequent analysis. By dividing the DR record into four chunks to remove the jump effects, the analyzed waveform could be recorded only up to 160 ms at 3 r/s.

**VEP analysis**

Effects of the pixel array replacement, or jump, appeared at a frequency that was twice the stimulus reversal rate. Only signals at the reversal rate were analyzed in the present paper because this frequency contains the signal specific for directional responses. Relevant response frequencies were first extracted from the record using Fourier analysis. Mann-Whitney U test, a circular variance test of consistency of the signal phase (Moore, 1980) was then performed to test for the significance of VEP (Wattam-Bell, 1985). Any runs with p > 0.05 on the U test or a signal-to-noise ratio of <1.5 were discarded. 25 ms was subtracted from both the transient and calculated latency values to allow for the systematic software delay. ANOVA (multivariate and repeated-measures) were then performed using SPSS 18.0 (IBM, Chicago, IL).
Any peak after these times would not be detected using this method.

Phase-based calculated latency

The phase-based calculated latency did not require dejumping since it was derived only from the component of the response at the reversal frequency. To calculate apparent latency, the phase of the signal at the reversal frequency at each temporal frequency was measured. As there are infinite series of phase values separated by 360°, phase was unwrapped. First, the difference between two adjacent temporal frequencies’ phases was calculated. Multiple(s) of 360° were subtracted from the phase value of the higher temporal frequencies until the difference became negative. The unwrapped phase values were then plotted against temporal frequencies. Finally, the slopes of their linear regression were converted into apparent latency by the formula:

$$\text{Latency (ms)} = \frac{\text{Phase} \Delta}{\text{Temporal Frequency} \Delta} \times \left( \frac{1000 \text{ ms}}{360^\circ} \right) - 25 \text{ ms Software Delay}$$

(Lee et al., 2012a) (Figure 4).

Results

To test the validity and reliability of using latency as a measure to track motion processing, response rates of the adults and infants were quantified. First, unlike other studies using the PR-VEP (Lee et al., 2012a) and OR-VEP (Lee et al., 2012b), an early transient peak within the time window of 50–100 ms with similar amplitude as the P1 (around 2 μV in adults and 0.9 μV in infants) was found in some of the subjects. When the early peak has equivalent amplitude to P1 (within one
standard deviation), the early peak was manually selected and included in the subsequent data analysis.

**Proportion of participants giving significant VEP responses**

Out of 61 adults that were tested, 29 (47.5%) yielded records from which a peak latency could be obtained with a statistically significant response at the reversal frequency based on the Mann-Whitney U test; 44 (72.1%) had significant phase measurements from which latency could be calculated, and 24 (39.3%) had additional early transient P1s that were easily identifiable. In total, 26 (42.6%) adults had records that yielded both transient and calculated latencies, while 22 (36.1%) adults had records yielding three latencies (Table 1).

Among the 76 infants tested, 27 (35.5%) infants showed significant components at the reversal frequency that yielded peak values, 37 (48.7%) yielded calculated latencies, and 13 (17.1%) infants showed additional early transient P1s. While 17 (22.4%) infants showed both transient and calculated latencies, only 9 (11.8%) infants had significant components at the reversal frequency for all three latencies (Table 1). To test the relationship between the transient P1 latency and phase-based calculated in DR-VEP, multivariate ANOVA was performed for the two measures separately.

**Transient P1 latency**

The more prolonged waveform for DR compared to PR (Lee et al., 2012a) and OR (Lee et al., 2012b) meant that the response to a reversal was not complete by 250 ms. In the 4 r/s recording, therefore, the transient peak

### Table 1. Response rate and number of adults and infants in each of the nine age groups with significant responses in transient, calculated, early transient, both transient and calculated, and all three latencies.

<table>
<thead>
<tr>
<th>Age (weeks)</th>
<th>Tested</th>
<th>Transient</th>
<th>Calculated</th>
<th>Early transient</th>
<th>Transient and calculated</th>
<th>All three latencies</th>
</tr>
</thead>
<tbody>
<tr>
<td>7.7–9.9</td>
<td>4</td>
<td>1</td>
<td>2</td>
<td>1</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>10–14.9</td>
<td>7</td>
<td>6</td>
<td>7</td>
<td>5</td>
<td>3</td>
<td>2</td>
</tr>
<tr>
<td>15–19.9</td>
<td>3</td>
<td>3</td>
<td>2</td>
<td>2</td>
<td>3</td>
<td>3</td>
</tr>
<tr>
<td>20–29.9</td>
<td>10</td>
<td>4</td>
<td>10</td>
<td>0</td>
<td>3</td>
<td>0</td>
</tr>
<tr>
<td>30–39.9</td>
<td>10</td>
<td>5</td>
<td>6</td>
<td>1</td>
<td>4</td>
<td>1</td>
</tr>
<tr>
<td>40–49.9</td>
<td>15</td>
<td>3</td>
<td>3</td>
<td>3</td>
<td>2</td>
<td>2</td>
</tr>
<tr>
<td>50–59.9</td>
<td>11</td>
<td>1</td>
<td>4</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>60–69.9</td>
<td>9</td>
<td>1</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>70–79.0</td>
<td>7</td>
<td>3</td>
<td>3</td>
<td>1</td>
<td>2</td>
<td>1</td>
</tr>
<tr>
<td>Infants total</td>
<td>76</td>
<td>27</td>
<td>37</td>
<td>13</td>
<td>17</td>
<td>9</td>
</tr>
<tr>
<td>Adults total</td>
<td>61</td>
<td>29</td>
<td>44</td>
<td>24</td>
<td>26</td>
<td>22</td>
</tr>
</tbody>
</table>

Figure 4: Illustration of the slope method to calculate apparent latency for an adult (A) and a 11.3-week-old infant (B). This adult was tested with nine different temporal frequencies from 1 to 16 r/s ($R^2 = 0.94$, slope = $-94.1$, latency = $-(-94.1) \times 1000/360 - 25 = 236.4$ ms (25 ms was the correction for software delay). The infant was tested with four different temporal frequencies from 2 to 6 r/s. The 11.3-week-old had $R^2 = 0.98$, slope = $-112.37$ /reversal rate, latency = 286.9 ms.
was likely to be confounded with the response to the preceding stimulus, and this reversal rate, unlike for PR and OR, could not be taken as contributing to the estimate of transient latency; instead it has to be treated as a frequency for steady-state analysis only.

The mean transient P1 latency for the adults was 126 ms; the infants showed marked age variation that is discussed below.

VEP waveforms from low temporal frequencies were more complex than the classical PR response, in which P1 is prominent and easily identifiable (Figure 3). Nine of the 22 (40.9%) adults who showed significant transient responses showed a more prominent early peak (with higher amplitude) of 91.7 ± 4.6 ms instead of the later peak of 125.6 ± 4.8 ms. Four of the 27 (14.8%) infants (12.4–79.0 weeks) had the early transient peak being more prominent than the later peak. ANOVA with latency methods as a within-subject variable showed that the latency of the later P1 was significantly longer than the latency of the early peak in adults. \( F(2, 42) = 0.1, p = 0.9 \). In infants, however, the difference was insignificant when age was taken as a between-subjects factor, \( F(5, 25) = 0.5, p = 0.8 \), which is an indication that age accounts for most of the latency difference.

In adults using temporal frequencies as the within-subject variable, ANOVA (Welch) showed no significant differences between the transient latencies for DR at low temporal frequencies (1, 2, and 3 r/s), \( F(2, 36) = 3.8, p = 0.1 \), and for that of early peaks, \( F(2, 42) = 0.1, p = 0.9 \), at these frequencies. Similarly for the infant group, with age as a covariate factor, no significant difference was found between the transient latencies at 2 and 3 r/s, \( F(1, 24) = 0.001, p = 0.98 \), or for the interaction effect between temporal frequencies and age, \( F(1, 24) = 2.2, p = 0.1 \). For the early peaks in infants, the latencies at 2 and 3 r/s were not significantly different, \( F(1, 13) = 0.6, p = 0.5 \); nor was the interaction between temporal frequencies and age, \( F(1, 13) = 2.1, p = 0.2 \).

For the subsequent analysis, the average of P1 latencies at the three temporal frequencies in each adult and two temporal frequencies in each infant were defined as the transient latency. Unlike the PR stimuli (Lee et al., 2012a), 4 r/s gave the equivalent of a steady state response in the direction reversal stimulus. The DR response to 4 r/s started to exhibit quasi-sinusoidal waveforms rather than complete VEP waves with clear peaks and troughs in respond to individual stimulus events.

**Phase-based calculated latency**

In both adults and infants, the slope method proved effective in calculating an apparent latency value of 194.9 ± 6.2 ms (Figure 4). For the 11 temporal frequencies that ranged from 1 to 16 r/s, a single linear fit between phase and temporal frequencies was found. This was consistent with other studies of PR-VEP (Fiorentini & Trimarchi, 1991; Tobimatsu, Tashima-Kurita, Hiromatsu-Nakayama, & Kato, 1991; Di Russo & Spinelli, 1999; Lee et al., 2012a) and OR-VEP (Lee et al., 2012b). The absence of any evidence of split slopes suggests that the difference between transient and calculated latency methods was not simply a result of different temporal frequency ranges, as in the parallel measurements for PR (Lee et al., 2012a).

Similar to PR (Lee et al., 2012a) and OR (Lee et al., 2012b), apparent latency can be calculated using just two temporal frequencies. In infants, ANOVA (with age as a between-subject factor) comparing the calculated latency derived from the 21 infants with only two temporal frequencies versus those infants with more than two temporal frequencies showed no significant difference between results obtained from the two data sets, \( F(1, 31) = 0.04, p = 0.8 \), nor any significant interaction between age and method, \( F(1, 31) = 0.1, p = 0.7 \) (Figure 5A).

To measure the developmental course of DR latency, both transient and calculated latency were analyzed in the adult and infant groups.

**Adults**

The mean transient P1 latency ± SE for the adults was 122.9 ± 1.8 ms, 87.2 ± 2.0 ms for the early transient P1, and 194.9 ± 6.2 ms for the calculated latency. Using latency methods as the within-subject variable, repeated-measure ANOVA (Greenhouse-Geisser) showed significant differences among the three methods, \( F(2, 42) = 103.40, p < 0.001 \) (Figure 6A and 6B). Calculated latency was significantly longer than the transient P1 latency, \( F(1, 25) = 77.7, p < 0.001 \). This was similar to the relationship in the adults’ OR responses (Lee et al., 2012b) but different from the PR (Lee et al., 2012a).

**Infants**

The transient response to DR was prolonged in infants compared to adults (Figure 3), just as in the PR (Lee et al., 2012a) and OR (Lee et al., 2012b) studies. The onset of DR-VEP was around 7.7 weeks for the calculated latency and 10 weeks for the transient latency, much later than the 3–4 weeks for the OR (Braddick, 1993), and around birth for the PR responses (Moskowitz & Sokol, 1983; Porciatti, 1984; McCulloch et al., 1999) but comparable with the findings of Braddick et al.
The infants were divided into nine age groups (Table 1). Repeated-measure ANOVA (age as a between-subjects factor) revealed significant effects on age on the transient P1, early peak, and calculated latencies, $F(2, 8) = 49.6, p < 0.001$, but no significant interaction effect of the three methods and age groups, $F(8, 8) = 1.8, p = 0.2$ (Figure 7A, B). Using latency methods as the within-subject variable, repeated-measure ANOVA
for the transient and calculated latencies also revealed a similar pattern: significant difference for the method, $F(1, 11) = 68.4, p < 0.001$) but not for the interaction between the two methods and the age groups, $F(5, 11) = 1.7, p = 0.2$.

**Comparison between infants and adults**

Both adults and infants had significantly longer calculated latencies than their transient latencies. Post hoc analysis (Games-Howell) revealed that the infant transient and early transient latencies were not significantly different from the adult values at the onset of the DR response, which is around 10 weeks of age ($p = 0.8$). However, infant calculated latency was similar to adult values only after 30 weeks of age ($p = 0.3$) (Figure 5B).

The average mean latencies in infants suggest that most of the drop in transient latencies was within the first 30 weeks of life (Figure 4A, B). Linear regression

Figure 6: Scatter plot of adult (A) calculated phase-based latency against transient P1 latency ($N = 26, R^2 = 0.0$) and (B) early transient latency against transient P1 latency ($N = 25, R^2 = 0.2$). The 45° angle line shows equality of the latency measures (slope of 1); so that for points above this line the calculated latency is greater than the measured P1 latency.

Figure 7: Scatter plot of infant (A) calculated phase-based latency against transient P1 latency ($N = 16, R^2 = 0.03$) and (B) early transient latency against transient P1 latency ($N = 11, R^2 = 0.6$).
was then fitted between latency and age from 10 to 27 weeks (Figure 8). The latency values showed a significant linear trend for only the transient latency, \( r = 0.8, F(1, 14) = 17.4, p = 0.001 \), latency = \(-5.1 \times \text{age} + 235.6\), with no such significant linear component for the calculated latency due its large variance.

**Discussion**

These experiments examined the maturation of directional motion responses in human infants through two approaches to VEP latency. The transient peak indicated the initial onset of such responses, while the phase-based calculated latency reflected the timing of the whole waveform.

**Transient P1 latency**

Unlike classical PR responses, in which P1, typically around 100 ms, is easily identifiable, the transient direction-selective response for DR exhibited a peak with smaller amplitude around 126 ms in adults (Figure 3). This is in contrast to our findings on another aspect of cortical selectivity, the OR response (Lee et al., 2012b). In that case, the adult P1 was a short latency as it was for pattern reversal, suggesting that the first detectable cortical response is orientation selective. Direction selectivity, in contrast, appears to require further processing time before it is manifest in the cortical response. This may reflect the fact that motion processing intrinsically requires the integration of information over time, since a directional displacement can only be recognized by combining information from successive positions of the stimulus.

The transient P1 latency in infants was higher than for adults, but not significantly so. This pattern is different from that found for PR and OR responses (Lee et al., 2012a, 2012b), suggesting that the initial processing of motion direction, although having a later postnatal onset than that for orientation (Braddick et al., 2005) is relatively mature at an early stage in its emergence.

**Transient early peak**

In a substantial proportion of adult (39.3%) records, an additional early peak appeared around 92 ms. A speculative possibility is that this peak represents a pathway for motion information to extrastriate areas that bypasses V1.

Single-cell recording has showed that different hierarchical levels were simultaneously activated by visual stimuli (Mountcastle, 1998). There is evidence for pathways to MT/V5 from a route bypassing V1 through pulvinar (Kaas & Lyon, 2007), a similar pathway, suggested to carry fast responses to motion, from the superior colliculus to area V3 (Lyon, Nassi, & Callaway, 2010), and a direct projection from the LGN to V5/MT (Sincich, Park, Wohlgemuth, & Horton, 2004). The role of such pathways is supported by the finding of V5/MT activation, and motion perception, in blind-sight patients without functional V1 (Stoerig & Cowey, 1997; Barbur et al., 1993; Goebel, Muckli, Zanella, Singer, & Stoerig, 2001). It has been proposed that this pathway is fast relative to the pathway through V1 (Ffytche, Guy, & Zeki, 1995), although there is counter evidence to this view (Azzopardi, Fallah, Gross, & Rodman, 2003).

Our electrode montage did not permit differential localization of various components of the response. It would be of interest to follow up these results with a high-density sensor array, to determine whether the scalp topography of the early peak differed from that of the regular P1 as would be expected if the former had an extrastriate source.

This additional early peak is much harder to detect in infants, and was shown by only 17% of all the infants tested. If it does represent the response of a direct extrastriate pathway, it suggests that the functional development of this pathway is relatively late. However, the early transient peak seemed to follow the developmental course of P1, in the sense that it could be found across the whole infant age range tested in this study (Figure 5A, B).

**Phase-based calculated latency**

Unlike the transient P1 latency that is determined by the timing of the initial directional response in the
cortex, the phase-based calculated latency reflects the entire time course of processing seen in the complete VEP waveform.

The longer calculated latency seen in adults indicates processing time beyond the initial detection of direction-reversal (Figure 5A, B), which includes timing needed to generate and process the entire VEP wave. These additional processes may be associated with horizontal connections (Gilbert & Wiesel, 1989; Nauhaus et al., 2009) between the direction-selective cells, recurrent and inhibitory loops between V1 and extrastriate visual areas, nonlinear transformation between V1 and extrastriate visual areas (Geisler & Albrecht, 1995), and integration time of spatiotemporal features (Lamme & Roelfsema, 2000). Such processes are likely to play a key role in the refinement of the direction-selective response and its modulation by contextual information.

**Development of phase-based calculated latency**

The calculated latency for direction reversal has a delayed developmental course in comparison with the transient P1 latency. This is similar to our findings with the response to PR (Lee et al., 2012a) but not for OR (Lee et al., 2012b). The calculated latency in DR reached adult values at approximately 30 weeks of age. Yet both the transient and early transient latencies were similar to their respective adult values at the response onset at approximately 8–10 weeks of age (Figure 4A, B). This is in line with the idea that the extended processing that elaborates the direction-specific response, indicated by the calculated latency, requires a longer developmental course to organize the lateral and recurrent connections that underlie it. Findings on the spatial distribution of VEP responses to transitions from coherent to incoherent motion (Wattam-Bell et al., 2010) suggest that there is a radical reorganization of the circuits underlying these responses between age 5 months and adulthood, perhaps a further reflection of developmental changes in these pathways, which may include frontal as well as posterior connections (Saron, Schroeder, Foxe, & Vaughan, 2001).

For the initial 30 weeks of life, the linear decrease in DR latency of 5.1 ms per week is steeper than that found for OR (4.2 ms per week; Lee et al., 2012b), suggesting a more rapid initial maturation of motion before form processing. This is consistent with results on infants’ responses to global form and motion (Braddick et al., 2003; Wattam-Bell et al., 2010).

The time course of latency maturation can be considered in relation to other findings on the development of motion processing. Rosander and von Hofsten (2002) found that at 2 months or 8.7 weeks of age, infants were able to generate smooth pursuit eye tracking of a moving object. This early motion response is similar to the 8–10 weeks of onset age found in this study and in Braddick et al. (2005). Nonetheless, the small decrease of peak latencies may be largely because of the progression of myelination with age (Magoon & Robb, 1981; Kos-Pietro, Towle, Cakmur, & Spire, 1997; Tsuneishi & Cahaer, 1997, Dubois et al., 2008). Layer 4B in V1 has a high incidence of directionally selective cells, which are also highly sensitive to contrast and velocity (Hawken, Parker, & Lund, 1988). Horizontal connections within layer 4B mature around 4 months or 17 weeks postnatal (Burkhalter, Bernardo, & Charles, 1993), which is much longer than the 8–10 weeks onset age found in the present study.

Using the same age range, the progression of DR transient latency is comparable to that of PR (Lee et al., 2012a) and OR (Lee et al., 2012b). However, DR calculated latency showed longer developmental delays in comparison to that of PR (Lee et al., 2012a) and OR (Lee et al., 2012b). DR having the longest calculated latency may serve as another indication of additional processing time contributed by two possible routes: (a) a shortcut from subcortical area to MT and (b) V1 to MT. The recurrent and feedback loops in both routes may explain the additional overall VEP processing time.

**Response rate**

Among the 61 adults and 76 infants studied in this paper, 48% adults yielded significant P1 latency, 72% for the calculated latency, and 39% for the early P1. In infants, 36% had significant P1 latency, 49% for the calculated latency, and 17% for the early P1. This relatively low response in comparison to PR-VEPs and OR-VEPs presumably reflects the relatively low amplitude in the DR case (mean of 2.4 $\mu$V for adults in comparison to 3.2 $\mu$V for PR and 2.9 $\mu$V for OR). In the case of the low frequencies used for the transient measurement, it also reflects the relatively lower signal-to-noise ratio at these frequencies. For infants the difference in amplitude is even larger (DR = 0.9 $\mu$V, PR = 12.3 $\mu$V, OR = 7.2 $\mu$V). Presumably averaging a greater number of cycles would improve the proportion of participants yielding significant results. However, the focus in this study was to obtain responses at a wide range of temporal frequencies within the time available, and less emphasis was placed on obtaining significant signals at the slower TF required to measure where P1 transient latency.

For infants the difference in amplitude is even larger, as DR produces 0.9 $\mu$V while PR has an average of 12.3 $\mu$V and OR has an average of 7.2 $\mu$V.
Factors affecting latency

Infant data showed an overall higher variance than that of adults. This was especially evident for the calculated latency of infants (Figure 6A). This is in line with other studies. Positron emission tomography scans (Hasnain, Fox, & Woldorff, 1998), magnetoencephalography studies (Bundo et al., 2000), and statistical analysis using distributed electrical source imaging have all found large individual variations in motion sensitive areas.

Since speed is a key variable for motion stimuli, and the temporal properties of the visual system are known to change with age, the developmental transition may also be speed dependent. Using translational motion VEPs, Lorteije, van Wezel, and van der Smagt (2008) showed that ventral areas are selectively activated by low speeds (3.5 deg/s) while dorsal areas are activated by both high (32 deg/s) and low speeds with two neural populations. As the DR stimulus used in this study has a constant low speed of 5.5 deg/s, the VEP responses probably originate from both the ventral and dorsal areas. This speed was chosen since it has been found to show the earliest developing responses in infancy (Wattam-Bell, 1996)

Like other VEPs, the latencies of DR responses is expected to depend on physiological factors such as myelination and axon properties (Buchner, Weyen, Frackowiak, Romaya, & Zeki, 1994; Wood & Allison, 1981), intracortical connections (Bullier, Hupé, James, & Girard, 1996), and feed-forward and feedback loops (Hupé et al., 1998; Tovee, 1994). DR may also depend on head circumference (Zhao & Pan, 2008), specific stimuli conditions tested that includes different contrast, temporal frequencies (Tobimatsu, Kurita-Tashima, Nakayama-Hiromatsu, Akazawa, & Kato, 1993a; Simon, 1992), and spatial frequency (Tobimatsu, Tashima-Kurita, Hiromatsu-Nakayama, & Kato, 1993b). Attention of the participant could also affect VEP latency (Di Russo & Spinelli, 1999; Di Russo, Martinez, Sereno, Pitzalis, & Hillyard, 2002; Ling & Carrasco, 2006).

Conclusions

Similar to PR-VEPs and OR-VEPs, the phase-based calculated latency of DR was much more prolonged compared to its transient P1 latency. Unlike PR-VEPs and OR-VEPs, DR responses also had an earlier transient peak that may reflect an additional processing route from the subcortical to the MT area. While the peak latencies may be mature at their response onset at 8–10 weeks of age, the temporal sequence of cortical motion processing appears not to be fully developed until after 8 months of age. A better understanding of DR-VEP may serve as a future clinical tool to detect abnormalities of motion development, which have been identified as a consequence of premature birth (Birtles et al., 2007) and other neurodevelopmental problems and may be relevant to other visual and biomedical disorders in infancy.

Keywords: direction reversal, visual evoked potentials, visual development, infant, phase

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