Binocular VEP Summation in Infants and Adults With Abnormal Binocular Histories

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Visual evoked potentials (VEPs) were recorded under binocular and monocular viewing conditions in 19 2- to 10-month-old infants, 19 stereodeficient adults, and 12 normal adults. VEPs were elicited by medium contrast, phase-alternated checkerboards with check sizes ranging from 10–52 min of arc. Binocular VEP summation was defined as the percentage by which the binocular VEP amplitude exceeded the mean of the two monocular VEP amplitudes. In the stereonormal adults, binocular VEP summation was significantly greater than zero and significantly less than 100%. In the stereodeficient adults, binocular VEP summation was not significantly greater than zero. These findings support the hypothesis that the magnitude of binocular VEP summation reflects the activation of binocular cortical neurons. However, binocular VEP summation in the infants averaged approximately 95%. Moreover, infants under 5 months of age, many younger than the reported age of onset for stereopsis, showed binocular VEP summation of nearly 145%. The significantly higher level of binocular VEP summation in the infants was the result of much larger binocular VEP amplitudes, while monocular VEP amplitudes were equivalent to those of stereonormal and stereodeficient adults. These results support the hypothesis that VEP amplitude is mediated by two independent pools of monocular cortical neurons and that binocular VEP amplitude in stereonormal and stereodeficient adults saturates at a lower level than in infants. Thus, it is hypothesized that binocular VEP summation is not representative of the activation of binocular cortical neurons.

Performance on a variety of psychophysical tasks is better under binocular viewing conditions than under monocular viewing conditions. If this binocular superiority is greater than the effect of probability summation, then neural integration of binocular inputs, or binocular summation, can be inferred. The absence of binocular summation in adults deprived of normal binocular inputs because of strabismus provides the strongest evidence that binocular summation is mediated by binocular cortical neurons.

Despite extensive research on binocular summation in adults, few systematic investigations have been conducted on human infants. There are two reasons why studies of binocular summation in young infants could prove to be important. First, several recent reports have demonstrated that stereopsis does not emerge in normal infants until the fourth postnatal month. These findings, along with additional evidence, are consistent with the hypothesis that the postnatal emergence of stereopsis coincides with the onset of functional cortical binocular neurons. Alternatively, binocular neurons may be present in young infants prior to the emergence of stereopsis, but above-chance performance on tests of stereopsis may be prevented by attentional deficits, grossly inaccurate binocular alignment, or other task demands that are not overcome until later in infancy. The development of more sensitive assessment techniques may reveal the presence of binocular summation prior to the reported onset age of stereopsis. Thus, if the presence of binocular neurons could be inferred from the presence of binocular summation, and if binocular summation emerged prior to the onset age of stereopsis, one could conclude that a necessary neural substrate for stereopsis was present prior to above-chance performance on tests of stereopsis.

A second reason for investigating binocular summation in young infants is the need for accurate and reliable indices of binocular functioning in patients with ocular anomalies, such as strabismus and amblyopia. Although a variety of clinical measures of binocular functioning are available for use with verbal children and adults, recently developed tests of
stereopsis in infants may be relatively time-consuming and require the absence of gross ocular misalignments. Because the level of binocular functioning is often used to guide the treatment of ocular anomalies, a rapid assessment that does not require accurate binocular alignment would be advantageous, particularly if it were possible to determine whether functional cortical binocular neurons were present in strabismic infants prior to corrective surgery.

These two reasons for studying binocular summation in young infants, one aimed at determining if cortical binocularity is present prior to the onset age of stereopsis, and the other aimed at determining if preverbal infants with ocular anomalies have functional cortical binocular neurons, both suggest the use of the visual evoked potential (VEP). If the VEP does accurately measure functional binocular vision, then it has enormous potential as a diagnostic tool. Conversely, if the VEP does not measure binocularity, then its use in binocular testing must be qualified. Unfortunately, assessments of binocular summation in normal, strabismic, and amblyopic adults using the VEP have provided both varying definitions of summation and inconsistent results. As noted earlier, psychophysical evidence of binocular summation consists of binocular performance that exceeds monocular performance by a factor greater than 1.4 (probability summation for two independent channels reduces the variance by \( \sqrt{2} \)). In the VEP literature, however, binocular summation has been given a variety of names, including summation, addition, and facilitation. The specific definitions of these names varies considerably depending on the experimental condition or calculation used.

Despite these inconsistencies, some general trends have emerged. Normal adults tested with phase-reversed patterned transient VEPs yield binocular VEP amplitudes consistently greater than either of the two monocular VEP amplitudes, although rarely greater than the sum of the monocular amplitudes. Significant levels of amblyopia (an interocular acuity difference of two or more octaves) are characterized by little or no enhancement of the binocular VEP amplitude over the larger of the two monocular VEP amplitudes. Amigo et al used the Incremental Binocular Amplitude (IBA), to measure the difference between monocular and binocular VEP amplitudes. The IBA is the percentage difference between the binocular VEP amplitude and the larger of the two monocular VEP amplitudes. Amigo et al found widely varying amounts of binocular VEP summation in infants and children between the ages of 2 months and 12 years. Moreover, because low levels of binocular VEP summation tended to be correlated with abnormal binocular experience, Amigo et al concluded that this application of VEPs would provide "...an objective method for screening out defects of binocular vision."

There are two problems associated with the Amigo et al study (see also Campos and Chiesi). First, although all subjects with normal stereopsis showed significant binocular VEP summation, some subjects without measurable stereopsis, including many infants under 4 months of age, showed significant levels of binocular VEP summation. Thus, binocular VEP summation, as assessed by their IBA index, appears to be a necessary, but not sufficient, correlate of the typical clinical criterion of normal binocular function (i.e., stereopsis).

Second, the IBA index is based on the superiority of the binocular VEP amplitude over the larger of the two monocular VEP amplitudes. Amigo et al used only the larger of the two monocular VEP amplitudes, because their normal subjects' monocular VEP amplitudes did not differ by more than 10%. However, other researchers have reported much larger interocular differences in the VEP amplitudes of amblyopes, with the amblyopic eye typically showing the lower amplitude. Therefore, if the difference in monocular VEP amplitudes is consistently more than 10%, the logic of the IBA must be reexamined. Using the larger of the two monocular VEP amplitudes always yields the smallest, most conservative estimate of binocular VEP summation, because it ignores the contribution of the amblyopic eye. Conversely, using the smaller of the two monocular VEP amplitudes yields the largest,

\[ \text{IBA} = \frac{\text{Binocular VEP amplitude} - \text{Larger monocular VEP amplitude}}{\text{Larger monocular VEP amplitude}} \times 100 \]

\( \text{IBA} \) is the percentage difference between the binocular VEP amplitude and the larger of the two monocular VEP amplitudes. If the VEP does accurately measure functional binocular vision, then it has enormous potential as a diagnostic tool. Conversely, if the VEP does not measure binocularity, then its use in binocular testing must be qualified.
most inflated estimate of binocular VEP summation, because it ignores the contribution of the non-am
blyopic eye. A measure of binocular function should relate the combined information obtained from both
eyes to the information obtained individually from the two eyes. Apkarian et al^{24} devised an alternate index
of binocular VEP summation that expresses the binocular VEP amplitude relative to the mean of the
monocular amplitudes.‡ Other researchers have used this measure^{28} and similar indices^{9.29-31} to evaluate
binocular VEP summation in normal and strabismic adults. As in the Amigo et al^{23} study, these reports have
demonstrated that binocular VEP summation is extremely variable and is not consistently present in
adults with strabismus, amblyopia, and/or suppression. Thus, it appears that the results on binocular VEP
summation, regardless of the index used, do not parallel the psychophysical evidence that supports the absence
of binocular cortical neurons in strabismic adults.

These variable findings and interpretations in stereodeficient adults, together with the limited data on
binocular VEP summation from young infants, make it important to determine the relation between bin-
ocular VEP summation and stereopsis in these two populations who presumably lack binocular cortical
neurons. If binocular VEP summation is always present in stereonormal adults and never present in stereode-
ficient adults, then stereopsis and binocular VEP summation would appear to share the same underlying
 mechanism. If binocular VEP summation is always present in stereonormal and stereodeficient adults, then
stereopsis and binocular VEP summation would not appear to share the same mechanism. If binocular VEP
summation is always present in stereonormal adults and never present in stereodeficient adults, but present in only some stereodeficient adults, then again there would appear to be at least two underlying
mechanisms. Finally, if infants younger than the onset age for stereopsis show binocular VEP summation, and
if the neural mechanism for stereopsis is absent prior to this age, then separate mechanisms must underlie
binocular VEP summation and stereopsis.

These possible relations between binocular VEP summation and stereopsis were assessed by measuring
VEP amplitudes in infants younger than the onset age for stereopsis, infants older than the onset age for ste-
reopsis, stereonormal adults, and stereodeficient adults. It is important to note that, despite differences in the
VEP waveform between infants and adults,^{34-41} large
and reliable VEPs can be recorded from young infants
if the eliciting stimuli are of sufficient contrast and size.

Materials and Methods

Subjects

Nineteen infants between 73 and 305 days of age were recruited by letter and by phone from the Bloom-
ington, Indiana, area. An additional 11 infants were excluded from the final sample because of failure to
complete the testing sessions due to crying, restlessness, or an intolerance of the eye patch. Infants were divided
into a young (< or = 140 days, n = 9) and an old (> or = 160 days, n = 10) age group.

Adult subjects were recruited from newspaper ads (19 adults with a history of strabismus) and existing
laboratory records (12 normal adults). An additional two strabismic adults were excluded from the sample
when it was determined that their strabismus was confounded by other factors. Specifically, one had retro-
lental fibroplasia and a detached retina, and the other had optic nerve atrophy. The remaining adults with a
history of strabismus were classified as small angle strabismics (<10 prism diopters lateral deviation with or
without amblyopia, n = 7), esotropic (ETs) (>10 prism diopters convergent or vertical deviation with or
without amblyopia and with and without alternating suppression, n = 8), and exotropic (XTs) (>10 prism
diopters divergent deviation with alternating suppression, n = 4). These classifications were based on patient
histories and on diagnoses performed on the day of testing. Details of these subjects’ histories, as well as
their deviations and acuities at the time of testing, are presented with their summation scores in Table 1.
Subjects were paid $5 for each visit. Informed consent was obtained from each subject, or from a parent of
the subject, after the procedure had been explained in detail and before testing began.

Procedure

VEPs were recorded from each subject using three
gold Grass electrodes placed (a) along the midline 1–
2 cm anterior to the inion, (b) on one earlobe as ref-
ence, and (c) on the other earlobe as ground. Imped-
ances, checked before testing and between each trial,
remained below 15 kOhms (x stereonormal adult = 7.59, sd = 3.82; x infant = 5.40, sd = 2.73; x ster-
edeficient adult = 5.97, sd = 3.76). VEPs were ac-
cumulated by, and stored in, a Nicolet CA-1000 signal
averager (Nicolet, Madison, WI) containing an artifact
rejection mode which eliminated any sweeps contami-
nated by blinks, head movements, or other transient
artifacts. The signal averager defined an artifact as any
signal that deviated more than 95% from the amplitude
of the cumulative mean. Pilot data and other work^{42}
‡ To illustrate the difference between this index of binocular VEP
summation and the IBA used by Amigo et al,^{23} consider the following
hypothetical VEP amplitudes: OU = 12 μV, OD = 8 μV and OS = 10 μV. The IBA index would be (12–10)/10 × 100 = 20%, whereas
the Apkarian et al^{24} index would be 1.33, and the Nuzzi and Franck^{29}
modified index would be [12 – [(10 + 8)/2]]/[(10 + 8)/2] × 100
= 33%.
Table 1. Characteristics of subjects with abnormal binocular histories

<table>
<thead>
<tr>
<th>Group</th>
<th>Sub.</th>
<th>Deviation</th>
<th>OD error</th>
<th>OS error</th>
<th>TNO score</th>
<th>Summation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Small Angle</td>
<td>5*</td>
<td>none</td>
<td>+.25-.75 X 180</td>
<td>+.50-.50 X 180</td>
<td>&gt;1980°</td>
<td>16.17</td>
</tr>
<tr>
<td></td>
<td>8*</td>
<td>ET</td>
<td>x</td>
<td></td>
<td></td>
<td>&gt;1980°</td>
</tr>
<tr>
<td></td>
<td>10*</td>
<td>ET</td>
<td>+1.75-.1 X 180</td>
<td>+3.25-.75 X 180</td>
<td>60°</td>
<td>-18.21</td>
</tr>
<tr>
<td></td>
<td>11*</td>
<td>none/amb</td>
<td>+6.0-.75 X 120</td>
<td>+.60-.125 X 135</td>
<td>&gt;1980°</td>
<td>52.39</td>
</tr>
<tr>
<td></td>
<td>15*</td>
<td>ET</td>
<td>-.50-.50 X 180</td>
<td>+.50-.50 X 180</td>
<td>&gt;1980°</td>
<td>4.33</td>
</tr>
<tr>
<td></td>
<td>18*</td>
<td>ET</td>
<td>+4.0-.4 X 100</td>
<td>+4.0-2.0 X 105*</td>
<td>&gt;1980°</td>
<td>23.21</td>
</tr>
<tr>
<td></td>
<td>19</td>
<td>none/amb</td>
<td>+4.0-.50 X 90</td>
<td>-1.5-1.0 X 20**</td>
<td>30°</td>
<td>19.72</td>
</tr>
<tr>
<td>ET</td>
<td>1</td>
<td>accom ET</td>
<td>+4.5-.75 X 20</td>
<td>+4.25-.25 X 180</td>
<td>480°</td>
<td>34.59</td>
</tr>
<tr>
<td></td>
<td>2</td>
<td>ET</td>
<td>+75-.1 X 10</td>
<td>plano-50 X 135</td>
<td>&gt;1980°</td>
<td>x</td>
</tr>
<tr>
<td></td>
<td>3*</td>
<td>ET</td>
<td>-1.0-.50 X 160</td>
<td>-.50-.1 X 180*</td>
<td>&gt;1980°</td>
<td>298.82</td>
</tr>
<tr>
<td></td>
<td>7</td>
<td>ET/amb</td>
<td>-4.0-.50 X 170</td>
<td>-.7-.5 X 130°</td>
<td>x</td>
<td>20.64</td>
</tr>
<tr>
<td></td>
<td>12</td>
<td>ET/amb</td>
<td>-.30-.50 X 90</td>
<td>-.75-.75 X 120°</td>
<td>&gt;1980°</td>
<td>131.83</td>
</tr>
<tr>
<td></td>
<td>14*</td>
<td>ET</td>
<td>+75-.5 X 180</td>
<td>+2.0-.1 X 175°</td>
<td>x</td>
<td>57.75</td>
</tr>
<tr>
<td></td>
<td>16</td>
<td>hypotrop</td>
<td>-.50-.25 X 150</td>
<td>-.75-.50 X 180</td>
<td>&gt;1980°</td>
<td>19.82</td>
</tr>
<tr>
<td></td>
<td>17*</td>
<td>ET/amb</td>
<td>+2.25-.1 X 180</td>
<td>+.75-.50 X 180</td>
<td>&gt;1980°</td>
<td>50.00</td>
</tr>
<tr>
<td>XT</td>
<td>4</td>
<td>alter XT</td>
<td>-1.5-.20 X 180</td>
<td>-3.0-.175 X 180</td>
<td>&gt;1980°</td>
<td>-30.86</td>
</tr>
<tr>
<td></td>
<td>6*</td>
<td>alter XT</td>
<td>-.2-.1 X 75</td>
<td>-.2-.5 X 90°</td>
<td>&gt;1980°</td>
<td>-39.30</td>
</tr>
<tr>
<td></td>
<td>9*</td>
<td>alter XT</td>
<td>-.175-.5 X 100</td>
<td>-.2-.5 X 55*</td>
<td>&gt;1980°</td>
<td>53.52</td>
</tr>
<tr>
<td></td>
<td>13</td>
<td>alter XT</td>
<td>plano-.75 X 180</td>
<td>+.75-.180°</td>
<td>&gt;1980°</td>
<td>-9.76</td>
</tr>
</tbody>
</table>

x unavailable data
* Strabismus surgery
* Refractive prescription

indicated that 50 sweeps, in our case, of 250 msec each, were sufficient to obtain a reliable VEP signal.

Infants were held on a parent's lap in a chair positioned 1 m from a 25-inch black and white television monitor (visual field size of 27° x 23°). An experienced observer utilized a hand-operated interrupt switch which was hard-wired to the signal averager to halt the averaging process when the infant looked away from the screen or started to cry. This observer also manipulated small, noisy toys in front of the television screen to maintain the infant's attention. The observer stood to one side of the monitor and could easily judge the direction of the infant's gaze. Adult subjects sat in a chair at the same distance from the screen.

At the end of each viewing condition, the observer monitoring the infant's gaze during data collection provided a judgment of the infant's overall attentiveness (1 = highly attentive, 2 = cooperative with occasional lapses of attention, 3 = very uncooperative). Most viewing conditions yielded acceptable scores (44%, 51%, and 5% of 1's, 2's, and 3's, respectively). Records with an attention level of 3 were not included in the data analysis. When possible, data dropped because of inattention were replaced by data collected on a subsequent session.

The stimulus display was a black and white checkerboard§ with an average luminance of 2.5 ft lamberts (8.58 cd/m²) and a contrast of 0.50. These values were similar to earlier work. All samples were collected with the room lights off. The checkerboard pattern was phase-reversed at a rate of 1.88 alternations per second (0.94 Hz). Check size was 26 min and 52 min for the infants and 10 min and 26 min for the adults. These check sizes were chosen to present one pattern that was clearly above each subject's threshold for producing a clear VEP signal, and one pattern that was near or below threshold (for infant acuity thresholds see Dobson and Teller, 45 Teller46). The smaller of the two check sizes was 26 min and 52 min for the adults. These values were similar to earlier work. All samples were collected with the room lights off. The checkerboard pattern was phase-reversed at a rate of 1.88 alternations per second (0.94 Hz). Check size was 26 min and 52 min for the infants and 10 min and 26 min for the adults. These check sizes were chosen to present one pattern that was clearly above each subject's threshold for producing a clear VEP signal, and one pattern that was near or below threshold (for infant acuity thresholds see Dobson and Teller, 45 Teller46). The smaller of the two check sizes used with adults (10 min) was the smallest check size the display system could generate at the 1 m viewing distance, and was clearly above threshold for most adults. Adults were tested while wearing their refractive correction.

Each subject was first tested under binocular conditions (OU) while viewing the larger of the two patterns. If a significant VEP amplitude was not obtained, impedances were checked and, if necessary, the check size was increased by one octave. If a consistent but small VEP amplitude was obtained, the check size was not changed. If a consistent and large VEP amplitude was obtained, the check size was decreased by one octave.

After collecting this initial OU VEP and selecting a check size, a minimum of three additional VEPs

§ A checkerboard pattern was used instead of a horizontal or vertical grating because it provided more contours to attract the infants' attention, it has been utilized in other infant studies, 45-46 and pilot work with normal adults indicated that with our protocol, stimulus display and electrode placement, a checkerboard pattern elicited a larger and more consistent response than did gratings (for a similar finding using flash VEPs, see MacKay & Jeffreys45).
Fig. 1. The percentage of binocular VEP summation shown by normal adults, infants, and stereodeficient adults as a function of check size. Bars = 1 SE.

were obtained in each complete session. These three VEPs consisted of (a) binocular viewing, (b) monocular viewing by the left eye (OS), and (c) monocular viewing by the right eye (OD). The order of these three conditions was randomized across subjects. In the monocular conditions, the nonviewing eye was covered with a black patch. If the infant remained cooperative after this set of four VEPs, a second set of four was collected using the next smaller check size. Alternatively, the second set was collected on a subsequent session. Both sets of VEPs were collected from all adults on the same day.

In addition to the VEPs, a dynamic near retinoscopy was performed on all subjects. A 12-inch black and white television monitor, located 1 m from the subject, presented a portion of a movie or cartoon from an RCA videodisc to attract and maintain the infant’s attention. The brightness and contrast levels of this movie matched the checkerboard pattern, and the retinoscopy was performed at the same distance (1 m) as the checkerboard. The purpose of this retinoscopy was to determine if the subjects were accommodating accurately to the stimulus distance (±0.50 D), if there was a gross difference in the refractive error between the two eyes (± 1.0 D), or if any spectacle correction worn by the adults was adequate. All subjects met these criteria.

Adults were also tested for their near Snellen acuity and their stereopsis using the TNO test. The performance of the two adult groups on the TNO test was compared to determine if the adult subjects with a history of strabismus were, in fact, stereodeficient. As seen in Table 1, it was not possible to compare mean thresholds on this task because 14 of the adults with abnormal binocular histories could not detect the depth in any of the TNO targets (maximum disparity = 1980 sec). In contrast, 10 of the 12 adults with normal histories had stereacuities of 60 sec or better. When the scores on the TNO were divided into what would constitute normal (60 sec or better) or worse than normal (480 sec or worse) scores, there was a significant deficit in stereopsis in the adults with abnormal binocular histories compared to the normal adults ($X^2 = 17.11, P < .001$). The group of adults with abnormal histories will subsequently be referred to as stereodeficient adults. Although we did not obtain stereopsis estimates from the infants, summary data compiled by Teller suggest that, based on the ages of the infants, only 63% would have shown evidence of stereopsis.

The binocular summation index devised by Apkarian et al. and modified by Nuzzi and Franchi compares the binocular VEP amplitude to the mean monocular VEP amplitude, and was used throughout the present report. Figure 1 shows these mean binocular VEP summation scores for the stereonormal adults, the infants, and the stereodeficient adults at the three check sizes. Multiple comparisons using Dunn’s procedure revealed that the infants showed a significantly greater amount of binocular VEP summation than either the stereonormal or the stereodeficient groups on the only comparable check size of 26 min (overall $P < .05$).

The group differences in binocular VEP summation shown in Figure 1 were also reflected in the individual subject scores. These scores were divided into the three categories of binocular VEP summation described by Nuzzi and Franchi (Table 2), and revealed different distributions across the normal adults, stereodeficient adults, and the combined infant groups ($X^2 = 9.493, P < .05$ for the 26' check size common to all groups). Most subjects, regardless of group, showed summation (scores between 0 and 100%), indicating a binocular VEP amplitude that was greater than the mean monocular amplitude, but less than twice as large. It is important to note that high summation scores (near 100%) were neither the result of large interocular differences in monocular VEP amplitude nor the result of a zero-amplitude VEP in one eye (monocular VEP amplitudes were all > 1 $\mu V$). However, the groups differed in that more stereodeficient adults showed inhibition (scores less than 0%), indicating a binocular VEP amplitude
that was less than the mean monocular amplitude, and more young infants showed facilitation (scores greater than 100%), indicating a binocular VEP amplitude that was more than double the mean monocular amplitude. Unlike Nuzzi and Franchi's results, some stereonormal adults showed inhibition scores, but only on the 26 min check size, and these scores were only slightly below zero (range: -0.40% to -12.91%).

Separation of the stereodeficient adults into the three clinical classifications (small angle, ET, and XT) revealed that none of these subgroups showed a significant amount of binocular VEP summation. Separation of the infant scores into a younger and an older age group revealed that the younger infants tested on the 52 and 26 min check sizes showed either summation (n = 7) or facilitation (n = 7). In contrast, none of the older infants showed facilitation on either check size and one showed inhibition.

Figure 2 presents a further illustration of this difference between the two age groups of infants. The younger infants showed amounts of binocular VEP summation that were significantly different from 0 on both the 52 min (t = 2.66, df = 6, P < .05) and 26 min (t = 3.00, df = 6, P < .05) check sizes, while the older infants showed significant binocular VEP summation on only the smaller 26 min check size (t = 3.27, df = 6, P < .02). Multiple comparisons using Dunn's procedure indicated that the two infant age groups differed significantly from each other in the amount of binocular VEP summation shown on the 26 min check size (overall P < .05), but not on the 52 min check size. In addition, stereonormal adults showed a significantly smaller amount of binocular VEP summation than the younger group of infants on the 26 min check size (overall P < .05).

The much greater binocular VEP summation scores obtained from the infants could be the result of a smaller monocular amplitude or a larger binocular amplitude (or both). While the amplitude of VEPs tends to be higher in infants than in adults, Figure 3 shows that, under the present testing conditions, monocular VEP amplitudes did not differ by age. This similarity in monocular VEP amplitudes provides a baseline across groups from which the differences in the binocular amplitudes can be compared. As shown in Figure 3 for the 26 min check size common to all groups, it appears that the higher levels of infant binocular VEP summation are the result of larger binocular VEP amplitudes (F(3, 40) = 11.30, P < .001). Monocular VEP amplitudes were not significantly different between groups (F(3, 40) = 1.64, P = .19). Multiple comparisons using Dunn's procedure revealed

### Table 2. Number of subjects showing different categories of VEP summation

<table>
<thead>
<tr>
<th>Group</th>
<th>Check size</th>
<th>Facilitation</th>
<th>Summation</th>
<th>Inhibition</th>
</tr>
</thead>
<tbody>
<tr>
<td>Stereonormal</td>
<td>52't</td>
<td>-</td>
<td>7</td>
<td>0</td>
</tr>
<tr>
<td>(n = 12)</td>
<td>26's</td>
<td>0</td>
<td>11</td>
<td>0</td>
</tr>
<tr>
<td>Young Infant</td>
<td>52'r</td>
<td>3</td>
<td>4</td>
<td>0</td>
</tr>
<tr>
<td>(n = 9)</td>
<td>26's</td>
<td>4</td>
<td>3</td>
<td>0</td>
</tr>
<tr>
<td>Older Infant</td>
<td>52's</td>
<td>0</td>
<td>3</td>
<td>1</td>
</tr>
<tr>
<td>(n = 10)</td>
<td>26's</td>
<td>0</td>
<td>7</td>
<td>0</td>
</tr>
<tr>
<td>Stereodeficient</td>
<td>52's</td>
<td>0</td>
<td>3</td>
<td>1</td>
</tr>
<tr>
<td>(n = 19)</td>
<td>26's</td>
<td>2</td>
<td>11</td>
<td>5</td>
</tr>
<tr>
<td></td>
<td>10's</td>
<td>1</td>
<td>11</td>
<td>7</td>
</tr>
</tbody>
</table>

Note: Missing data points are due to infants' sessions which were discarded because of poor attention, infants who contributed one good session and could not return to the laboratory because of scheduling conflicts or illness, and one adult's session which was interrupted by mechanical failure and could not be rescheduled.
younger infants showed facilitation of the binocular VEP (two infants on both check sizes, one on only the 26 min size). This discrepancy is not solely the result of the different indices used to compute binocular VEP summation. Using Amigo et al's more conservative index, four of our younger infants still showed facilitation (two infants on both check sizes and two more on only the 26 min size).

It is apparent from Figure 3 that the higher levels of binocular VEP summation among the infants are primarily the result of larger absolute binocular VEP amplitudes. These larger binocular VEP amplitudes are unlikely to be solely the result of attentional mechanisms. First, the reduction in binocular VEP amplitudes with age would imply a significant developmental decrease in attention. However, this implication is not supported by the behavioral ratings in the binocular condition, which averaged 1.25 in the younger infants and 1.41 in the older infants ($t = 1.47$, df = 75, $P = n.s.$). Second, the younger infants' monocular VEP amplitudes may have been depressed more than the older infants' because the eyepatch was more distracting. If so, the younger infants' behavioral ratings should have been poorer than the older infants'. In fact, the reverse was true, as 33% of the young infants' ratings in the monocular viewing conditions were assigned the highest score of "1," while none of the older infants achieved this rating while wearing the patch.

The second conclusion of the present study is that stereonormal and stereodeficient adults do not show the same pattern of binocular summation as measured by VEPs. The stereonormal adults showed both good stereovisual 52 min size, and two on only the 26 min size). This discrepancy is not solely the result of the different indices used to compute binocular VEP summation. Using Amigo et al's more conservative index, four of our younger infants still showed facilitation (two infants on both check sizes and two more on only the 26 min size).

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The second conclusion of the present study is that stereonormal and stereodeficient adults do not show the same pattern of binocular summation as measured by VEPs. The stereonormal adults showed both good stereovisual and a significant amount of binocular VEP summation, which was greatest at the smaller check size. The group of stereodeficient adults did not show a significant amount of binocular VEP summation, and these summation scores were only weakly correlated with stereovisual and a history of strabismus, a finding which supports some earlier reports. The range of binocular VEP summation scores observed in the stereonormal adults (−12.91–103.6%) was completely subsumed by the range of scores from the stereodeficient adults (Table 1). This variability, in combination with the weak correlation between binocular VEP summation and stereovisual or binocular history, renders binocular VEP summation a poor prospect as a clinical test of functional binocularity. These findings indicate that the type of binocular summation measured by VEPs may be an index of fusion independent of bifoveal fixation and strabismus, and that binocular VEP summation may not be a reliable predictor of the level of stereopsis.

Amigo et al did not find significant amounts of binocular VEP summation in their sample of 14 stereodeficient children and adults, but their overall scores

**Discussion**

The binocular VEP summation scores obtained in the present study support two major conclusions. First, infants showed more binocular VEP summation than either stereonormal or stereodeficient adults. Furthermore, younger infants showed more binocular VEP summation than older infants, despite the fact that many were younger than the reported mean onset age for stereopsis. This larger amount of binocular VEP summation is not due to the larger monocular and binocular VEP amplitudes generally found in infants, because the binocular VEP summation index is expressed as a ratio that is uninfluenced by absolute VEP amplitudes. These large binocular VEP summation scores, particularly in the younger infants, contrast markedly with the findings of Amigo et al. Only one of their nine infants under 5 months of age showed scores greater than 100%, whereas five of our nine younger infants showed facilitation of the binocular VEP (two infants on both check sizes, one on only the 26 min size, and two on only the 26 min size). This discrepancy is not solely the result of the different indices used to compute binocular VEP summation. Using Amigo et al's more conservative index, four of our younger infants still showed facilitation (two infants on both check sizes and two more on only the 26 min size).
were lower than those in the present report. There are several possible explanations for this. First, Amigo et al.\textsuperscript{23} used slightly different contrast and luminance levels. Second, as noted earlier, Amigo et al.\textsuperscript{23} used a conservative statistic which was less likely to detect significant amounts of binocular VEP summation. Finally, Amigo et al.\textsuperscript{23} did not report whether their subjects were suppressors, although none were exotropes.

The finding that some stereodeficient adults do not show significant amounts of binocular VEP summation is consistent with psychophysical evidence supporting the hypothesis that binocular summation is mediated by binocular cortical neurons. However, the large amounts of binocular VEP summation found in the infants is inconsistent with that conclusion if these binocular cortical neurons are necessary and sufficient for stereopsis, and if the reported onset age of 4 months for stereopsis is correct. If binocular VEP summation were highly correlated with stereopsis, or if they shared the same neural mechanism, then young infants under the onset age for stereopsis should have less binocular VEP summation than older infants or stereonormal adults. Moreover, if binocular VEP summation were correlated with stereopsis, then binocular VEP summation would increase, not decrease, with age, and stereopsis and binocular VEP summation would be at least moderately correlated in stereonormal and stereodeficient adults.

Several researchers\textsuperscript{28,31} have suggested an alternative to the hypothesis that the larger VEP signal under binocular conditions is due to the excitation of binocular cortical neurons. Because there are cortical neurons that respond to inputs delivered to only the right or left eye, one could hypothesize two monocular pools of neurons whose overall firing pattern under binocular conditions is greater than under monocular conditions. This hypothesis is supported by the finding that binocular VEP summation was either absent or greatly reduced in subjects who suppressed one eye during binocular viewing conditions. While the present study did not test suppression during the collection of VEPs, the absence of binocular VEP summation in suppressors parallels findings by other researchers.\textsuperscript{45} Alternating suppression should result in the activation of, at most, one pool of monocular neurons, regardless of viewing condition. Thus, the expected binocular VEP amplitude in suppressors should never exceed either of the two monocular VEP amplitudes.

The hypothesis that binocular VEP summation may simply be due to the activation of a larger pool of cortical neurons under binocular viewing conditions could account for the results from our infants, stereonormal adults, and stereodeficient adults if we make the following assumptions. First, in early infancy, prior to the onset of stereopsis, the amplitude of the binocular VEP is approximately equal to the algebraic sum of the two monocular VEP amplitudes. This complete summation (equal to a binocular VEP summation score of 100%) results from the activation of two independent pools of monocularly driven cortical neurons. Second, after the fourth postnatal month, as the neural mechanism for stereopsis emerges, the contribution of the two pools of monocular cortical neurons to the amplitude of the binocular VEP changes. Specifically, there is an increase in the magnitude of interocular VEP inhibition elicited under binocular conditions. As a result, the binocular VEP in the normal, mature visual system is characterized by an interocular inhibition that effectively saturates the combination of the two monocular VEP amplitudes, resulting in binocular VEP summation scores below 100% but greater than 0%. Finally, some individuals with ocular anomalies develop even greater interocular inhibition than normals, resulting in binocular VEP summation scores of approximately 0%. The neural mechanism assumed to underlie this interocular cortical inhibition does not reside in the number or percentage of binocular cortical neurons (which mediate psychophysical binocular summation and stereopsis), but rather in the gating on and off of excitatory and inhibitory neurons in the cortex. Recent data on single unit and VEP recordings from cats indicate quite clearly that binocular VEP summation does not require the presence of binocular cortical neurons.\textsuperscript{50}

In conclusion, we have shown that binocular VEP summation is not correlated with the presence or level of stereopsis in infants, stereonormal adults, and stereodeficient adults. We have also shown that binocular VEP summation is considerably greater in younger infants than in older infants or adults. Finally, we have shown that some, but not all, stereodeficient adults show significant binocular VEP summation, despite the absence of stereopsis. One could account for these findings by proposing that binocular cortical neurons are required for binocular VEP summation, and that young infants and some strabismic adults who show binocular VEP summation do not show evidence of stereopsis because of factors other than the absence of binocular cortical neurons. However, the much greater amount of binocular VEP summation in young infants suggests that two independent pools of monocularly driven neurons are sufficient for significant levels of binocular VEP summation. We have hypothesized that the amplitude of the binocular VEP signal saturates at progressively lower levels in later infancy and adulthood as interocular cortical inhibition increases.

**Key words:** binocular summation, VEP, infants
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