Disparity Tuning of Binocular Facilitation and Suppression after Normal versus Abnormal Visual Development

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PURPOSE. To study the pattern of facilitatory and suppressive binocular interactions in stereodeficient patients with strabismus and in healthy controls.

METHODS. Visual evoked potentials were recorded in response to a Vernier onset/offset pattern presented to one eye, either monocularly or paired dichoptically with a straight vertical square-wave grating, which, when fused with the target in the other eye, gave rise to a percept of a series of bands appearing in depth from an otherwise uniform plane or with a grating that contained offsets that produced a standing disparity and the appearance of a constantly segmented image, portions of which moved in depth.

RESULTS. Participants with normal stereopsis showed facilitative and suppressive binocular interactions that depended on which dichoptic target was presented. Patients with longstanding, constant strabismus lacked normal facilitative binocular interactions. The response to a normally facilitative stimulus was reduced below the monocular level when it was presented to the dominant eye of patients without anisometropia, consistent with classical strabismic suppression of the nondominant eye. The dominant eye of strabismic patients without anisometropia retained suppressive input from crossed but not uncrossed disparity stimuli presented to the nondominant eye.

CONCLUSIONS. Abnormal disparity processing can be detected with the dichoptic VEP method we describe. Our results suggest that suppression in stereoblind, nonamblyopic observers is determined by a binocular mechanism responsive to disparity. In some cases, the sign of the disparity is important, and this suggests a mechanism that can explain diplopia in patients made exotropic after surgery for esotropia. (Invest Ophthalmol Vis Sci. 2009;50:1168–1175) DOI:10.1167/iovs.08-2281

In a natural scene, many features in the visual field will lie at different horizontal, and sometimes different vertical, positions in the two retinal half-images. Fusion converts the horizontal differences (disparities) to a stereoscopic depth, assigning each feature a unique three-dimensional position in visual space. Fusional mechanisms also change the visual direction so that the fused percept appears at a horizontal and a vertical location midway between the locations in the half-images. It is easy enough to work out the projected location and depth of a feature from the binocular geometry, but how does the binocular system implement this fusion process neurally? Viewed alone, the monocular location of the target is different from the binocular location. What happens to the neural responses to monocular location when the images are fused?

Numerous psychophysical studies have demonstrated that information in the monocular half-images is lost during normal fusion.1–4 In a study that is particularly relevant to this article, McKee and Harrad5 measured monocular Vernier acuity using a standard target that consisted of two vertical lines, presented one above the other. Predictably, thresholds for detecting misalignment were in the hyperacuity range (≤10 arcsec). However, thresholds rose dramatically when this target was paired stereoscopically with a Vernier target in the other eye containing a large fixed offset. Because of the large offset, the upper line appeared at a different depth from the lower line. Provided that the upper line remained fused binocularly (for offsets covering a range of 6 to 60 arcmin of disparity), thresholds were elevated, compared with the monocular Vernier threshold, by as much as 1 log unit. This “fusional suppression” is not a form of dichoptic masking. If the Vernier target is fused with a straight line in the other eye (0 offset), thresholds are very low because the binocular target is now essentially a stereocuity target.

Fusional suppression is probably part of the neural network that determines a unique stereoscopic match. A monocular target will weakly stimulate all disparity-tuned neurons that receive input from the target’s retinal location. When a matching feature is presented to the other eye that strongly excites neurons tuned to a particular disparity, these neurons may inhibit or suppress the weaker responses from neurons tuned to other disparities and locations. An inhibitory network of this type will enhance the correct match by reducing the competitors.

Previous work on healthy observers6 has found electrophysiological evidence for these inhibitory interactions. Using a variant of the McKee-Harrad stimulus, we presented an oscillating Vernier target in one eye and paired it stereoscopically with a static fusible target in the other eye (Fig. 1). The visual evoked potential (VEP) is particularly sensitive to the misalignment of contours or surfaces.7,8 The static target by itself elicited no VEP, but when fused with the oscillating Vernier target, it modulated the Vernier-driven response. The response was enhanced when paired with straight static lines (Fig. 1, middle) but was suppressed by the offset static target (Fig. 1, right). As in the psychophysical studies, binocular fusion of a disparate target suppressed the monocular VEP response, and the inhibitory interaction was dependent on the target disparity.

Because of the misalignment of their eyes during early development, most observers with strabismus have no functional stereopsis. Nevertheless, they do have binocular interac-
tions, primarily of a suppressive or an inhibitory kind. Harrad and Hess explored whether suppression could be explained as normal dichoptic masking with unequal contrast thresholds. They found that even when the difference in thresholds was taken into account, masking by the dominant (fixing) eye was greater than predicted from normal dichoptic masking functions. Strabismic suppression is not explained by dichoptic contrast masking, so it must involve some other form of binocular inhibition. Given that normal fusion involves suppression, strabismic suppression may be a residual component of the nonfunctional stereo system. That strabismic suppression is observed between similar contours only and that cross-oriented gratings presented dichoptically produce as much rivalry in strabismic observers as in nonstrabismic observers supports this idea.

In this study, we used the VEP to explore the electrophysiological characteristics of suppression in strabismic patients with and without anisometropia. We found evidence consistent with strabismic suppression as a component of an aberrant stereo network that, when operative, prevents diplopia in the absence of stereopsis. We also found a special case in which suppression failed in a disparity-dependent fashion.

Materials and Methods

Observers

Nine healthy adult observers with normal monocular and binocular vision and no previous history of amblyopia, patching, or intermittent strabismus consented to participate. Each observer had a corrected LogMAR visual acuity of 0 (20/20) or better in each eye and normal stereopsis on testing with TNO plates. We defined normal stereopsis as ≤20/200 arcsec; however, all healthy participants had a stereoacuity of ≤50 arcsec. Twenty-six patients with a history of abnormal visual experience during development because of either strabismus with anisometropia (n = 14) or strabismus without anisometropia (n = 12) participated. The stereoacuity of the patients ranged from 120 arcsec to unmeasurable. Patients were considered to be anisometropic if their spherical equivalent refractions differed by more than 0.75 diopters between the two eyes. Patients were considered to be amblyopic if their interocular acuity differed by 0.2 LogMAR or more. Local ethical committee approval was obtained, and each observer gave fully informed consent. The research complied with the principles of the Declaration of Helsinki.

Stimulus Generation and Apparatus

Details of the apparatus and basic signal acquisition and processing operations are described in detail in a previous publication and are described here only briefly. The active VEP display, described schematically in Figure 1, consisted of a circular image of 14° diameter. Computer-generated nonius lines for alignment in both the horizontal and the vertical planes were presented around the aperture, and the stimulus was further surrounded by a fusible pattern of small circles that aided accurate superimposition of the images. The observers were asked to physically align the nonius lines by movement of the mirrors and to regularly check their position between stimulus trials.

VEP Stimulation Protocol

Six stimulus conditions were presented to each eye. Each condition consisted of the same dynamic “test” stimulus presented to one eye, with one of three static images presented to the other eye. The stereoscopic condition consisted of an oscillating Vernier onset/offset stimulus presented to one eye and a mean luminance central field surrounded by the binocular fixation pattern presented to the second eye. In a second condition type (binocular disparity), the oscillating Vernier stimulus was paired with a static, collinear bar pattern. The Vernier offset created either crossed or uncrossed disparities. The third condition type (binocular 5 arcmin) was the same as the second, except that the static bar pattern also contained Vernier offsets that created a standing crossed or uncrossed-disparity pedestal of 5 arcmin. Crossed disparities will be referred to as positive numbers and uncrossed disparities as negative numbers. When presented alone, the static patterns did not produce a VEP response; but when fused with the temporally modulated pattern, they modified the healthy observ-
er's perception of the stimulus in terms of its position in the lateral and the depth domains.

The dynamic "test" pattern consisted of vertical randomly generated black and green bars of spatial frequency 1 ± 0.49 cyc/deg, with 80% contrast. The pattern was divided into 1° horizontal bands. An oscillating Vernier pattern was created by laterally shifting alternating bands back and forth, into and out of alignment with the static bands, at a frequency of 2 Hz (square-wave temporal profile). Over a trial period of 10 seconds, the Vernier offsets increased in size in 10 equal logarithmic steps from 0.5 arcmin to 10 arcmin.

When the test stimulus was combined with a blank mean luminance half-image, the observers perceived purely lateral displacement (Fig. 1, bottom). When combined with the straight static pattern (Fig. 1B), the displacement produced a horizontal disparity so that healthy observers perceived the oscillating bands appearing and disappearing in depth from a collinear background. The moving panels jumped to an apparent position that was either in front of or behind the static bands for crossed and uncrossed disparities, respectively. In the other binocular condition type, the static pattern was also divided into bands matching those in the dynamic pattern. These bands were assigned a constant lateral offset of ±5 arcmin in the direction opposite the offset in the dynamic pattern. Thus, as the Vernier oscillation swept from 0.5 to 10 arcmin, the disparity of the bands swept from 5.5 to 15.0 arcmin or −5.5 to −15.0 arcmin.

**VEP Quantification and Statistical Analysis**

The complex numbers representing the amplitudes and phases of the 2-Hz first harmonic of the evoked response were coherently averaged over all trials for each stimulus condition for each observer. Coherent averaging uses amplitude and phase information. Group averages were computed in a similar way. For example, the average sine and cosine coefficients were calculated across observers before magnitude was calculated. For the plots of response magnitude (Fig. 2), we computed an error measure by pooling the errors on the sine and cosine coefficients in quadrature, as has previously been done for single-observer averages.15 This measure assumes that the sine and cosine coefficients are uncorrelated. However, correlations occur between these measure-

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**Figure 2.** Disparity tuning functions for the first harmonic (1F) components for (A, B) participants with normal vision, (C, D) patients with strabismus without anisometropia, and (E, F) patients with strabismus and anisometropia. Data collected when the test was in the dominant eyes are plotted in the first column (dominant eye). Right: data collected when the test was in the nondominant eye. Gray filled circles: monocular data (Mon). Black filled squares: zero-disparity pedestal data (Bin0). Black open squares: five arcmin-disparity pedestal data (Bin5). (A, B) In the participants with normal vision, the first harmonic response of the 0-disparity pedestal data lies above the monocular data, but the 5 arcmin-disparity pedestal data lies below the monocular data. In each of the patient groups, facilitation in the Bin0 condition was reduced. Error bars were calculated by summing the errors on the sine and cosine coefficients computed across observers in quadrature.15
ments in the case of cross-observer averages because of the presence of individual differences in overall response amplitude. For significance testing, therefore, we used multivariate analysis of variance (MANOVA), which takes these correlations into account. MANOVA also correctly models the correlation structure of our repeated-measures design. When we plot data in the complex plane, we show two-dimensional standard errors (Fig. 3). These error bounds are often elliptical because of correlations between real and imaginary values that arise from individual differences in absolute amplitude. Note that these errors are the same as those that would be computed for a between-subjects design and that they do not reflect the within-subject errors used to assess significance when the MANOVA was used to compare responses across conditions measured within a given group. In all the statistical evaluations, we used the last bin of the sweep to test for effects of stimulus condition because this bin generally had the largest response across conditions and observer group.

**RESULTS**

Periodic Vernier onset/offset stimuli produce odd and even harmonic responses that increase monotonically with offset size.\(^6,7,14\) The current analysis focuses on the first harmonic component of the response because previous work has shown this component to be selective for relative position in the case of lateral motion\(^7\) and the disparity of dichoptic targets.\(^6\) The second harmonic responses were also examined in the present study, but they did not show clear disparity effects.

The data will be presented in two formats. First, VEP amplitude will be plotted as a function of the magnitude of the swept parameter (displacement) for ease of visualization of amplitude effects. Second, because the spectral analysis yields phase and amplitude information, the data will be re-plotted in the complex plane so that both amplitude and phase effects can be visualized. Statistical evaluation will be performed on the complex values.

**Effects of Disparate Pedestals in Healthy Observers**

In healthy observers, the addition of a zero-disparity, collinear pedestal leads to a larger first harmonic response than that recorded under monocular viewing conditions.\(^\left( F(2,7) = 5.9; P = 0.031 \right)\), replicating previous reports with similar stimuli.\(^6,14\) This effect can be seen in Figures 2A and 2B by comparing the monocular data (gray filled circles; Mon) to the binocular zero-disparity pedestal data (black filled squares; Bin0). In this condition, there is a motion-in-depth percept in addition to the perceived alternation between a collinear set of bars and a segmented set in the monocular condition.

The disparate-pedestal condition (Figs. 2A, 2B, black open squares; Bin5) produces a lower amplitude response than does the monocular condition or the zero-disparity pedestal condition, again replicating previous results.\(^6,14\) Although this condition also leads to a percept of motion in depth, it does not result in a perceived change of segmentation, even though the dynamic half-image alternates between collinear and noncollinear states (Fig. 1, bottom). The level of standing disparity thus controls the nature of the response to the dynamic test, leading to increases or decreases in response amplitude that are well modeled as gain changes.\(^1,4\)

**Combined Amplitude and Phase Effects**

Spectral analysis of the VEP yields amplitude and phase values for each level of the sweep. Figure 3 plots the data in the complex plane where distance from the origin corresponds to response amplitude. The time/phase origin for the plots is at the positive x-axis, and increasing phase lag/delay is in the counter-clockwise direction. Successive points on the tuning function are connected with lines.

As the size of the displacement increases, the response increases in amplitude. In addition, the response phase depends on the size of the displacement and on the type of pedestal in the other eye. As the magnitude of the monocular test offset increases, response phase progresses toward the phase origin of the plot, consistent with a speeding of the response as the stimulus becomes progressively suprathreshold. The addition of the zero-disparity pedestal preserves the same progression of phases seen in the monocular condition but with an increased magnitude response at each corresponding displacement (Fig. 3; compare magenta and dark blue circles). In contrast, the disparate-pedestal shifts all response

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**Figure 3.** Two-dimensional plots of the complex values underlying response amplitude and phase. The x-axis plots the real/cosine component, and the y-axis plots the imaginary/sine component in units of microvolts. Left two columns: data from the dominant eyes for uncrossed and crossed disparities. Right two columns: data from the nondominant eyes. Data from each observer group are presented as rows. Within each panel, the monocular data are plotted in blue, the zero-disparity pedestal data are plotted in magenta, and the disparate-pedestal data are plotted in orange. As amplitude increases, the response phase shifts toward the phase origin (in the clockwise direction), especially in the monocular and zero-disparity pedestal conditions. Ellipses: dispersion at a nominal 1 SEM.
phases toward the origin and reduces the amplitude of the response (Fig. 3, orange circles). The effect of disparity (0 minute vs. 5 minutes) on the response amplitude is significant for each combination of eye and disparity sign in healthy participants (Table 1 for significance values).

**Effects of Disparate Pedestals in Strabismus Patients without Anisometropia**

In contrast to healthy observers, patients with constant strabismus and no anisometropia showed substantial differences in the pattern of responses between their dominant and nondominant eyes and differences between each of their eyes and either eye of healthy participants. These data are plotted in Figures 2C and 2D and in Figures 3e to 3h. These patients did not, in general, have amblyopia (9 of 11). We eliminated from the analysis the single patient in this group who had demonstrable stereopsis for comparability with the group of strabismic-anisometropic patients who had no demonstrable stereopsis.

**Monocular Condition.** Monocular response amplitudes in the nondominant eyes of this group of patients are approximately equal to those of the dominant eye, consistent with the relative lack of amblyopia in this group.

**Zero-Disparity Pedestal Condition.** When the dynamic test was in the dominant eye of patients in this group, there was no increase in amplitude in the zero-disparity pedestal condition compared with the monocular condition, unlike our healthy observers (Figs. 2C, 3e, 3f). Response amplitudes and phases were, in fact, similar to those measured in the monocular condition.

When the test was in the nondominant eye and the zero-disparity pedestal was in the dominant eye, the response was lower than in the monocular condition (Figs. 2D, 3g, 3h), though this effect did not reach significance ($F(2,9) = 2.24; P = 0.162$). However, when we compared the pattern of results in the monocular and binocular zero conditions between patients and healthy participants, there was a significant interaction effect between stimulus type and patient group ($F(2,17) = 7.66; P < 0.001$). The different relationship between monocular and zero disparity responses in the two groups is consistent with strabismic suppression replacing normal facilitation when the test was in the nondominant eye.

The reduced rather than enhanced zero-disparity pedestal response was also present in the smaller group of nine patients who did not have amblyopia. The reduction of the response to the test in the nondominant eye when the zero-disparity pedestal is presented to the dominant eye suggests that neither fusional suppression because the influence of this stimulus was decreased when the pedestal was in the nondominant eye (e.g., Fig. 2C).

When the test was in the dominant eye, the nondominant eye has a weaker effect (Fig. 2C). When the pedestal carried an uncrossed disparity, there was no difference between the zero-disparity pedestal and the disparate-pedestal conditions (Figs. 2C, 2D, 3e–h; Table 1) in 3 of 4 comparisons. The nondominant eye does, however, exert an effect on the dominant eye if the disparate pedestal has a crossed disparity (Figs. 2C [open squares], 3f). The effect is a small but significant reduction in amplitude over a range of suprathreshold disparities (Table 1). The dominant eye response was thus largely independent of the stimulus presented to the nondominant eye, with the exception of a small, suppressive input from crossed disparities.

**Effects of Disparate Pedestals in Strabismus Patients with Anisometropia**

**Monocular Condition.** Almost all the strabismus patients who were anisometropic also had amblyopia (12 of 14), and all had defective stereopsis. Consequently, there was a large overall difference in response magnitude between the dominant eyes and the nondominant eyes that did not occur in the other patient group (compare Figs. 2E, 2F). Monocular sensitivity differences at the first harmonic are correlated with perceptual measures of Vernier offset sensitivity and with letter acuity.**

**Zero-Disparity Condition.** The normal increase in amplitude in the binocular zero condition relative to the monocular response was absent when the test was in either eye (Figs. 2E, 2F, 3i–l), as was seen in the strabismus patients who did not have anisometropia. When the test was in the nondominant eye and the zero-disparity pedestal was in the dominant eye, the response did not differ from that of the monocular condition ($F(2,31) = 1.439; P = 0.253$).

**Disparate Pedestal Condition.** Overall, there were only small differences among the monocular, binocular zero, and disparate-pedestal conditions in the patients with strabismus and anisometropia (Figs. 2E, 2F, 3i–l). In only one condition (test in the dominant eye, crossed disparities; Fig. 3j; see Table 1) was there a significant difference between the disparate and nondisparate-pedestal conditions. This input from the nondominant eye was also present in the strabismus-only group (Figs. 2C, 3e). In the nondominant eye, the response to the disparate-pedestal condition was similar to that in the monocular condition (unlike the same eye of patients without anisometropia, who showed lower responses). Most of these eyes were amblyopic, and the lack of effect of either pedestal when presented in the dominant eye suggests that neither fusional nor strabismic suppression occurred in this patient group.

**Monocular Response Differences in Dominant Eyes**

Although the visual acuity of the dominant eyes of both patient groups was comparable, we noted a previously unreported difference in the overall phase of the dominant eye responses of the strabismus patients with and without anisometropia.
This is shown in Figure 4 for the monocular responses of each group. The curves of the strabismus-only patients are shifted in the lag direction (counterclockwise) compared with those in anisometropic strabismus patients or healthy participants, and the responses in the strabismus-only group are slightly larger than those of patients with anisometropia. The combination of phase shifts and amplitude changes is significant in a between-subjects analysis ($F(2,22) = 4.49; P = 0.025$). The 30° phase difference between the two strabismic groups corresponded to approximately 30 to 40 ms. In other words, patients with pure strabismic amblyopia experienced a delay. Thus the dynamics of the monocular response of the dominant eye depended on the developmental history and status of the nondominant eye. The major sensory difference between the strabismic groups was the presence of amblyopia in the nondominant eye.

**DISCUSSION**

Our results suggest that suppression in stereoblind, nonamblyopic observers is determined by a binocular mechanism responsive to disparity. As in healthy observers, the effect of the static stimulus on the oscillating Vernier target depends on the disparity specified by the binocular configuration, though the normal facilitation by the zero-disparity Vernier target is absent. The differential effect of crossed and uncrossed-disparity pedestals on the dominant eye response of the observers with strabismus also argues for a disparity-tuned mechanism.

The disparity-dependent effects in the dominant eye of the strabismic patients are relevant to the clinical observation that patients who are esotropic and are made exotropic by surgery report double vision. Because of the esotropia, the patient will not have experienced crossed disparities and, therefore, might never have developed a mechanism to suppress images that carry them. By contrast, it would be necessary to have developed a means of suppressing the nearly constant presence of large uncrossed disparities to prevent diplopia. The haploscope allowed us to present crossed and uncrossed disparities in a controlled fashion and thus to observe a residual "unsuppressable" crossed input from the nondominant eye that affected the responses of the dominant eye. Three previous reports have been published of the nondominant eye having an effect on the dominant eye,10,17,18 but this is the first study to show the presence of disparity-tuned suppressive interactions.

In contrast to the preservation of suppressive interactions, we found that patients with longstanding, constant strabismus lack normal facilitative binocular interactions. This interaction is elicited in healthy observers in the zero-disparity pedestal condition, which adds a binocular disparity cue to the monocularly visible cues for discontinuity present in the monocular control condition. The same disparity cue that produces enhancement of the monocular response in healthy participants can result in a lower response in the patients, especially when the static pedestal is presented to the dominant eye of strabismic patients who do not have amblyopia (Fig. 2D). The trend for the responses of this normally facilitative stimulus to be reduced below the monocular level is consistent with classical strabismic suppression.

A recent psychophysical study found evidence for intact facilitative binocular interactions in patients with strabismic amblyopia.19 The authors were able to find these interactions after equating the contrast levels in the two eyes of the patients for distance above detection threshold. When they made this compensation, they found normal levels of binocular summation. Another study found evidence for facilitative binocular interactions in patients with strabismic amblyopia using a dichoptic masking task,20 though an earlier study did not find such evidence.21 Although contrast-sensitivity differences might have played a role in the loss of facilitation in our patients with amblyopia, it was unlikely that they were present in the group that did not have amblyopia. These patients also lost the facilitation conferred by the zero-disparity pedestal. Consistent with this, Lema and Blake20 found no evidence of binocular summation in stereoblind persons with equal contrast sensitivity in both eyes. Our nonamblyopic strabismus patients were probably similar to their stereoblind subjects. The degree to which residual binocular facilitation is present may depend on what function is being tested and the patient’s history of abnormal binocular interaction.

**Comparison with Previous VEP Measures of Binocular Interaction**

The paradigm we developed was designed to probe the pattern of disparity-dependent binocular interactions. Unlike other VEP paradigms for binocular interaction, such as summation indices25–27 or cyclopean random dot responses,28–37 we were able to separately assess the contribution of each eye to the interaction. This was possible because we effectively tagged each eye’s input with a different time course rather than using the same time course in each eye. Because one eye’s input is dynamic and the other eye’s input is static, the time-locked evoked response was labeled for the eye of origin. In this way, we could assay the inputs from one eye without directly recording an evoked response from it. In a traditional binocular summation paradigm, monocular responses are recorded from each eye separately, and the sum of these responses is compared with that measured when both eyes see the same image. This method can detect binocular interaction as an additive failure, but it cannot recover the separate contributions of each eye during binocular stimulation.

The timing format of our method was similar to that of other temporal tagging methods that examine binocular interaction under dichoptic conditions with the target in one eye static and the other dynamic.12,58–60 Other techniques use distinct temporal frequencies in each eye.12,58,60 With these
latter methods, responses of each eye are recorded simulta-
neously at harmonics of the respective eye-tagging frequencies, and
definitive evidence for binocular interaction can be ob-
tained by detecting responses at frequencies equal to sums and
differences of the eye-tag frequencies. The main difference
between our method and previous dichoptic tagging methods
was that we focused on binocular interaction in the network of
cells responsible for low-level detection of image discontinui-
ties. Our method is thus more focused on spatial relationships
than on the contrast processes that have been the focus of
previous studies. Our method also provides a measure of mon-
ocular Vernier acuity that can be used to quantify degree of
amblyopia.\textsuperscript{16}

## Timing Abnormalities in the Dominant Eyes

We observed an alteration in the response timing in the dom-
inant eyes of patients that depended on whether their strabis-
mus was accompanied by anisometropia. The dominant eyes of
the strabismus patients all had normal acuity; thus, reduced
spatial acuity was not a factor. At present we have no expla-
nation for the basis of this effect and simply report its pres-
ence. The altered response timing could be the result of several
factors: genetic or other constitutional differences between
anisometropic and nonanisometropic strabismus patients, dif-
fences in the pattern of binocular interaction, and differ-
ces in treatment history. Anomalies in response timing may
provide additional clues about the pathophysiology of strabis-
mus and amblyopia.

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