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Envelope size tuning for stereo-depth perception of small and large disparities

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Abstract

Stereopsis is the sense of depth derived from binocular disparities that are formed between targets that are matched between the two retinal images. Binocular matches for sustained stereopsis are based on similarity of orientation, spatial frequency and contrast of the two retinal images whereas matches for transient stereopsis depend on these parameters to a very limited extent. In this investigation we have tested the possibility that transient stereopsis forms matches between objects of similar overall size. The tuning of sustained and transient stereopsis to contrast-envelope size was investigated by presenting narrow-band Gabor targets of unequal size to the two eyes. Bandwidth for envelope-size tuning was estimated from the range of dichoptic size-differences over which stereo performance remained above chance level. An equal bandwidth of 2 octaves was found for the sustained and transient stereo systems when stimulated with parallel orientation Gabors that subtended a small disparity. Sustained-stereo performance with orthogonal carriers was reduced with large envelope sizes. Bandwidth of the transient stereo system increased to 3 octaves when tested with a larger disparity stimulus and it was independent of carrier orientation. Reducing the contrast of the larger-size Gabor improved transient-stereo performance from near chance (48–58%) to 85–95%. Thus the bandwidth for envelope-size tuning is much broader than indicated with equal physical contrast stimuli. The observed tuning to envelope size, while broad, is tighter than that observed for carrier spatial-frequency [Vis. Res. 38 (1998) 3057], carrier orientation [Vis. Res. 39 (1999) 2717] and contrast polarity [Vis. Res. 39 (1999) 4010] of the stimulus. Thus it would appear that envelope size and, to a greater extent, temporal synchrony of the dichoptic stimuli [Perception 24 (1995) 33] are the primary means for selecting matched binocular inputs for transient stereopsis.

Keywords: First order; Second order; Stereopsis; Transient; Sustained

1. Introduction

Disparity-based depth perception is mediated by at least two different mechanisms; a transient system and a sustained system. The transient system processes briefly-presented images that can range in disparity from small to highly diplopic, and it generates a brief (transient) impression of depth. The sustained system only processes relatively long-duration stimuli that are mainly within Panum's fusional area, and it generates a lasting (sustained) impression of depth (Schor, Edwards, & Pope, 1998; Edwards, Pope, & Schor 1999; Pope, Edwards, & Schor, 1999). While the sustained stereo system is tuned to orientation, spatial frequency and contrast of the two retinal images, the transient system does not require similar luminance information in the two retinal images to form binocular matches (Schor, Wood, & Ogawa, 1984a; Halpern & Blake 1988; Legge & Gu, 1989; Schor & Heckman 1989; Schor et al., 1998; Edwards et al., 1999; Pope et al., 1999). Vivid stereoscopic depth can be perceived with brief stimuli even when the detailed structure of the two retinal images differs markedly. Thus far the only matching cue that the transient system has been shown to use is the degree of temporal simultaneity of the two retinal images (Cogan, Konstevich, Lomakin, Halpern, & Blake, 1995). It is not clear if any spatial features of

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the stimulus are used to form binocular matches of transient stimuli. In this investigation we tested the possibility that the transient stereopsis system uses overall stimulus size as a binocular matching cue. The tuning of sustained and transient stereopsis to contrast-envelope size was investigated by presenting narrow-band Gabor targets of unequal size to the two eyes.

The broadband tuning of the transient stereo system to the carrier information is indicative of a second-order system (Cavanagh & Mather, 1989). Models of second-order processing typically involve four processing stages: initial filtering of the stimulus by standard first-order filters, non-linear transformation of these responses (e.g. full or half-wave rectification), pooling of these responses, and finally a second filtering-stage. Because the aim of the second filtering stage is to extract the spatially-localized contrast envelope of the stimulus, (i.e. the Gaussian envelope of a Gabor stimulus), the second filtering stage is tuned to a lower spatial frequency than the first (Wilson, Ferrera, & Yo, 1991b; Sutter, Sperling, & Chubb, 1995). Binocular matching can be based upon the information contained in these extracted (i.e. rectified) envelopes.

The main aim of the present study was to determine the degree to which the transient stereo system is tuned to the envelope size of stimuli. The existence of size tuning would demonstrate a spatial feature that was used by the transient system to form binocular matches. Tuning was tested at both small (0.5°) and large (5°) disparities. The small disparity was tested to allow us to directly compare the degree of envelope tuning of the transient and sustained systems, because both systems operate at small disparities (Pope, et al., 1999). However, stereopsis only responds to transient stimlui at large (highly diplotic) disparities (Ogle, 1952).

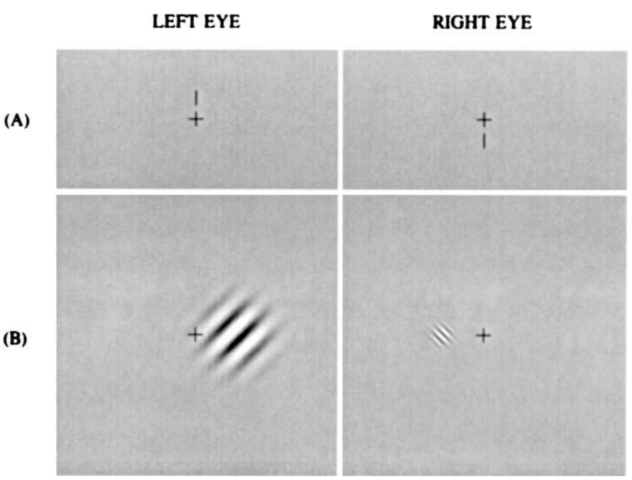

Fig. 1. (A) Fixation cross and nonius line. (B) An example of the test stimulus. The fixation pattern was replaced by the test stimulus for either 140 ms or 7 s. Each dichoptic image contained a Gabor patch presented in crossed or uncrossed disparity. Envelope-size tuning was examined for small disparities (Exp. 1), large disparities (Exp. 2), and contrast tuning (Exp. 3) of the Gabor stimuli.

2. Experiment 1: envelope tuning at small disparities

2.1. Methods

2.1.1. Observers

Three male observers were used, two of the authors (CS and ME) and an observer who was naive with respect to the aims of the experiment (ZZ). All subjects had corrected-to-normal visual acuity, normal stereopsis (as measured by a Randot Stereotest), and no history of any binocular visual disorders.

2.1.2. Stimuli and procedure

The luminance profile of the test stimulus was a Gabor function defined by:

$$L(x,y) = A \sin\{2\pi f(-x \sin\theta + y \cos\theta)\}\exp\left(-\frac{x^2+y^2}{2\sigma^2}\right) + M$$

where A is the amplitude of the function, f is the spatial frequency of the carrier grating, θ is the orientation of the grating, σ is the S.D. of the Gaussian envelope, and M is the mean luminance. The size of the Gabor patch will be quantified in terms of σ. The contrast of the stimulus is the ratio of the amplitude of the carrier to the mean luminance level. Sinewave carriers were presented in sine phase and the standard deviation of the Gaussian envelope varied from 0.25° to 2.5°. Carrier frequency was proportional to the envelope size (σ) of the Gaussian. Specifically, the carrier was the reciprocal of σ, in units of degrees, which produced, approximately, 4.5 visible cycles of the carrier in each envelope and a constant full bandwidth of 0.54 octaves at half height.

The fixation target and test stimulus are shown in Fig. 1A and B. Fig. 2 plots the amplitude spectrum for Gabor patches over a 3-octave range of envelope size (σ). The narrow bandwidth of the Gabor patch reduced the luminance spatial-frequency overlap of the unequal size dichoptic images as the difference between their size increased. Size tuning was measured with a reference or fixed-size Gabor that was presented to one eye while a variable-size Gabor was presented to the other eye. A small disparity of 0.5° was used so that the envelope size tuning of the transient and sustained systems could be compared directly. Note that we have previously shown that the transient system can process small (i.e. fusable) disparities (Pope et al., 1999).

The observer first maintained fixation on a pair of crosses, between vertically separated nonius lines, as shown in Fig. 1A. Once the observer had established fixation with the nonius lines aligned, he initiated the presentation of the test stimulus (shown in Fig. 1B). The test stimuli replaced the nonius lines and consisted of a pair of dichoptic Gabors. The Gabors were pre-

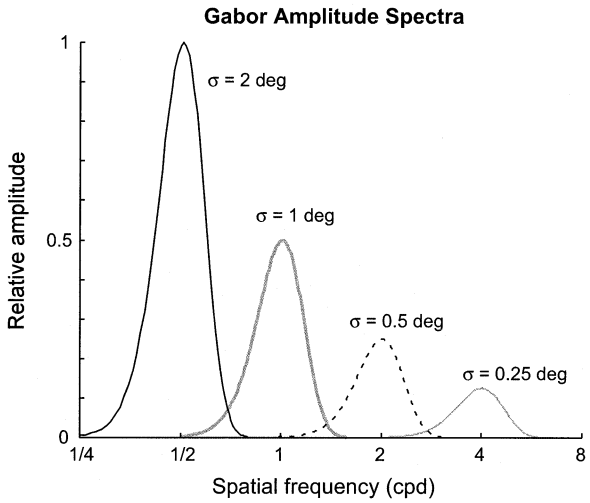

Fig. 2. Frequency spectra of Gabor patches whose envelope sizes vary over a 3 octave range.

sented at either crossed or uncrossed disparity relative to the depth of the fixation point. The observer's task was to indicate whether the Gabor was closer or farther than the fixation point. Observers received feedback concerning the validity of their response. The sinewave carriers of the Gabors were either parallel or orthogonal. In the parallel condition, the orientation of the carriers in the two dichoptic half-images was vertical. In the orthogonal condition, the carriers were oriented at 45° and 135°. The orientation difference of the orthogonal stimuli that is greater than the orientation range of first-order stereo processing (Blakemore, Fiorentini, & Maffei, 1972; Von der Heydt, Adorjani, & Hanny, 1977) thus precluding the involvement of a first-order system that directly matches the carrier information. The parallel condition was included in the event that bandwidth for envelope size-tuning depended on whether or not the carrier orientation was fusable.

We measured the percentage of the observer's correct responses. Observers had to perceive the depth of matched-size Gabors at a relatively high-level of performance in order have a large performance range over which to measure stereo performance with unmatched-size targets. The perceived separation of diplopic stimuli can be less than what is predicted by their physical disparity (allelotropia) (Rose & Blake, 1988), and the perceived separation of diplopic images can differ in the crossed and uncrossed direction. To ensure that differences in perceived horizontal separation of the diplopic Gabors were not used as a cue to the direction of depth, the magnitude of the disparity was jittered. This cue was more pronounced with the large disparity (5°) such as used in Experiment 2. Consequently, the amount of jitter needed to eliminate the allelotropia cue with a 5° disparity test stimulus was determined for each observer. This range was established by having the observers attempt to estimate depth by only using the perceived separation of the diplopic Gabors. The jitter range was increased until perceived separation was no longer correlated with perceived depth. The jitter disparity added to any given trial was randomly chosen from a set of three values. For ZZ and CS, these values were 0.1°, 0.15° and 0° and ME used half of these values because he was less sensitive to this cue.

These experiments used stimuli similar to those used by Pope et al. (1999) that were designed to selectively stimulate the sustained and transient systems. Pope et al. (1999) varied exposure duration and contrast amplitude of opposite-contrast Gaussians presented in a raised-cosine temporal window to control the stimulus energy at high and low temporal frequencies. Increasing stimulus duration and lowering contrast selectively increased low temporal frequency components and decreased high-temporal-frequency information. Increasing stimulus duration of the low contrast stimulus decreased the likelihood that the stimulus would activate the transient system and increase the likelihood that it would activate the sustained system. They found that the perception of stereo depth depended on the temporal-frequency composition of the temporal envelope. Stereo-depth with opposite-contrast Gaussians could be perceived with low contrast stimuli presented within a raised cosine temporal window with a short but not long duration. At high contrast levels, stereo depth could be perceived with both short and long exposure durations. If the opposite-contrast Gaussians were presented at a low contrast in a rectangular temporal window, stereo depth could be perceived with both short and long durations. These results illustrated that the transient system could process reversed contrast stimuli while the sustained system could not and selective stimulation of sustained and transient systems depended on temporal frequency composition rather than exposure duration.

The current study presented low-contrast Gabor patches within a rectangular temporal window of short duration (140 ms) and within a raised cosine temporal window of long duration (7 s). These exposure durations and temporal windows, together with the low luminance contrast of 25%, were used to selectively present high and low temporal frequencies to activate the transient and sustained systems, respectively (Pope et al., 1999). The mean luminance of the display, as viewed through our apparatus, was 3 cd/m^2. Four reference envelope sizes were used that corresponded to σ s of 0.25°, 0.37°, 0.75° and 1.25°. Each of these was paired with Gabors of other sizes that spanned a five-fold range. Stimuli were presented in blocks of 20 and 10 blocks were taken to compute performance.

2.1.3. Apparatus

Stimuli were generated using a Cambridge Research Systems VSG 2/3 graphics card in a host Pentium computer and were displayed on a custom model 3 Vision Research Graphics monitor. Sequential presentation of the dichoptic half-images to each eye was controlled with Vision Research Graphics ferro-electric shutters. The fast decay rate of the monitor's P46 phosphor (0.1 μs to 10% of the phosphor's initial luminance value) ensured that there was no interocular cross-talk via the shutters. The frame rate of the monitor was 120 Hz, so the effective frame rate to each eye was 60 Hz. At this frame rate no flicker was discernable. The observer initiated each trial and responded with a button box. A chin rest was used to stabilize the observer's head.

2.2. Results

The results for the three observers for the fixed small-disparity condition are shown in Figs. 3 and 4. Percent-correct is plotted against the variable-envelope size (σ) of the Gabors for both the long-duration (Fig. 3) and short-duration (Fig. 4) conditions. Symbols represent the different values of the reference Gabor size that was paired dichoptically with the variable Gabor sizes shown on the abscissa. Error bars represent plus and minus one standard error of the mean.

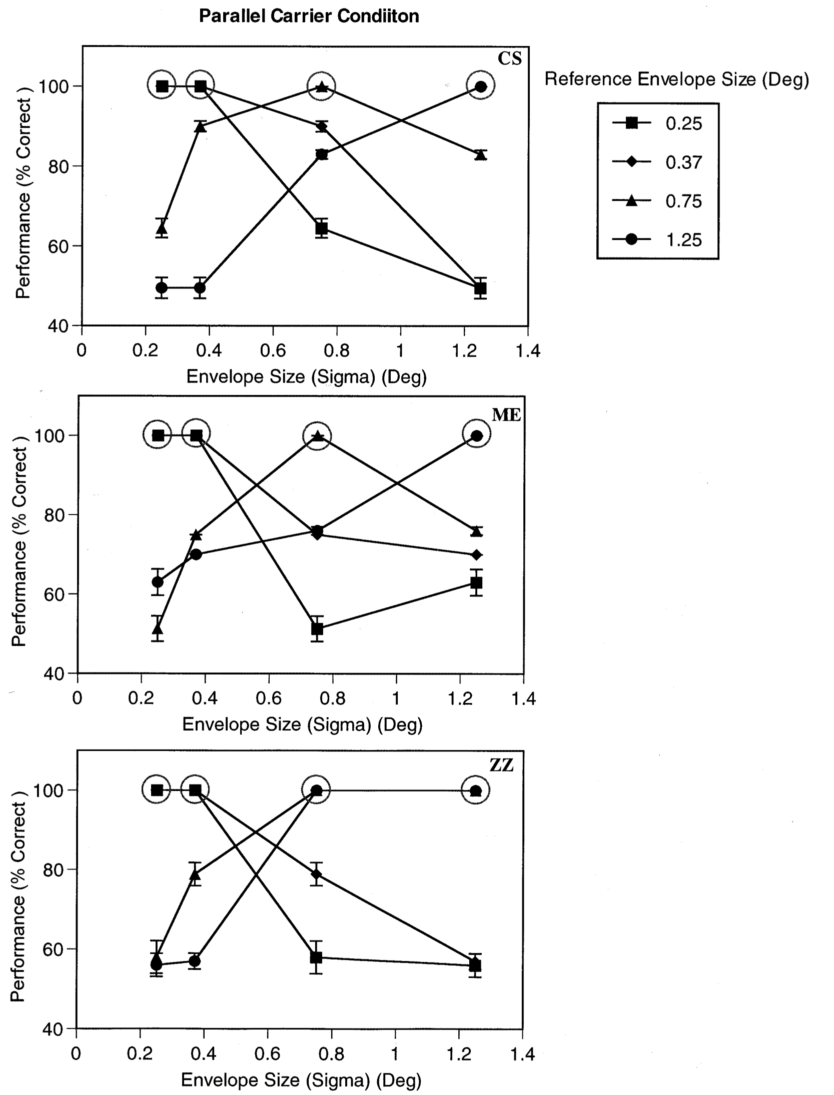

Fig. 3. (a, b) Results for the small disparity- sustained stimuli in Experiment 1. Percent-correct response for small 0.5° disparity stimuli presented for 7 s in a raised temporal cosine window, is plotted against variable envelope size (σ). Error bars represent plus and minus one S.E.M.. Four different σ s were paired dichoptically with variable σ s shown along the abscissa. The results for parallel and orthogonal carrier stimuli are shown in (a) and (b), respectively. Performance was highest when the Gabors were equal in size for both parallel and orthogonal orientations. Performance declined as envelope size increased and was near chance level for all orthogonal stimulus pairs containing large envelopes (1.25°). Circled symbols represent matched stimulus sizes presented to the two eyes.

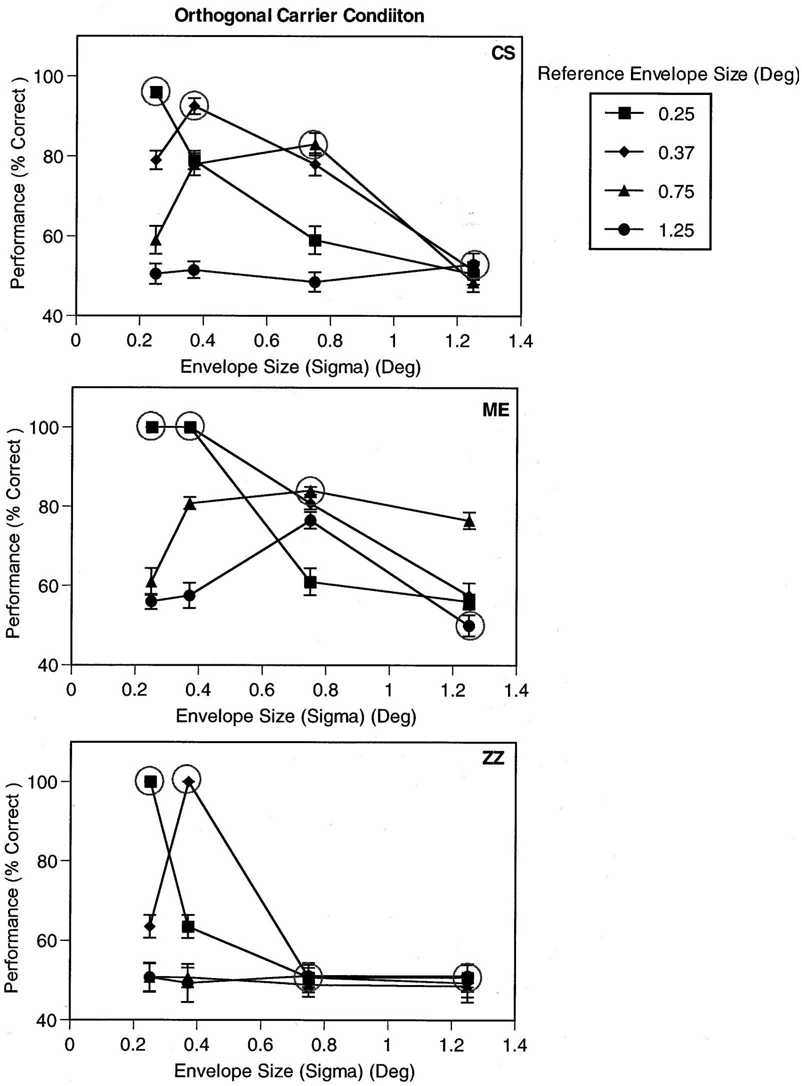

Fig. 3. (*Continued*)

For the long-duration, small-disparity condition (Fig. 3a and b), the basic pattern of results is substantially the same for all observers. For both the parallel (Fig. 3a) and orthogonal carrier orientations (Fig. 3b), performance by the sustained stereo system was always highest when the Gabors were equal in size. We define the bandwidth for envelope-tuning of the stereo system as the range of size differences over which stereo performance remained above chance level. For parallel orientations, performance for small and large envelopes decreased from 100% with matched sizes to near chance levels when size differences approached 2 octaves. For orthogonal orientations, performance depended upon the size of the reference envelope. With the smallest reference size (0.25°) all observers showed 100% performance levels with matched sizes. Performance decreased to chance levels when size differences approached 2 octaves. As the reference size was increased, performance levels decreased such that for the largest size used (1.25°) all observers showed chance-level performance even with matched sized Gabors. This reduction in performance with increasing reference size was most pronounced for observer ZZ. His performance was near chance for all orthogonal stimulus pairs containing large envelopes (0.75° and 1.25°).

It is noteworthy that when the envelopes were small, the observer could sense depth with orthogonal carrier orientations. The above-chance-level performance with long-duration, small, size-matched envelopes that contained orthogonal carrier orientations indicates that the sustained stereo system can extract envelope information with a (non-linear) second-order process that is tuned for size. The stereo response was evident even though the carrier orientations could not be fused into a single orientation percept or when portions of one carrier were suppressed. The reduced performance with the large envelope could have resulted from stronger binocular inhibitory interactions or rivalry between large orthogonal targets, as compared to the smaller targets.

The basic pattern of results for the small-disparity, short-duration condition (see Fig. 4a and b) is substantially the same for all observers. As with the long-duration sustained stimuli, performance by the transient system was always best when the dichoptic Gabors were equal in size. This pattern holds for both the parallel and orthogonal carrier orientations. For both the parallel and orthogonal conditions, performance for small and large envelopes decreased to near chance levels when size differences approached 2 octaves.

Comparison of stereo responses to sustained and transient stimuli reveal many similarities, but also one major difference. For the parallel-orientation stimuli, performance for the sustained and transient durations were essentially identical for all envelope sizes (compare Fig. 3a and Fig. 4a). For the orthogonal condition, while similar performance was obtained with small-envelope stimuli, there was a marked difference with the large-envelope stimuli. Performance with large-envelope orthogonal stimuli was at chance level for the sustained stimuli, while performance with the transient stimuli was well above chance levels (90–70% for the three observers; compare Fig. 3b and Fig. 4b). Note however, that performance for orthogonal transient stimuli was higher with matched small than large envelopes.

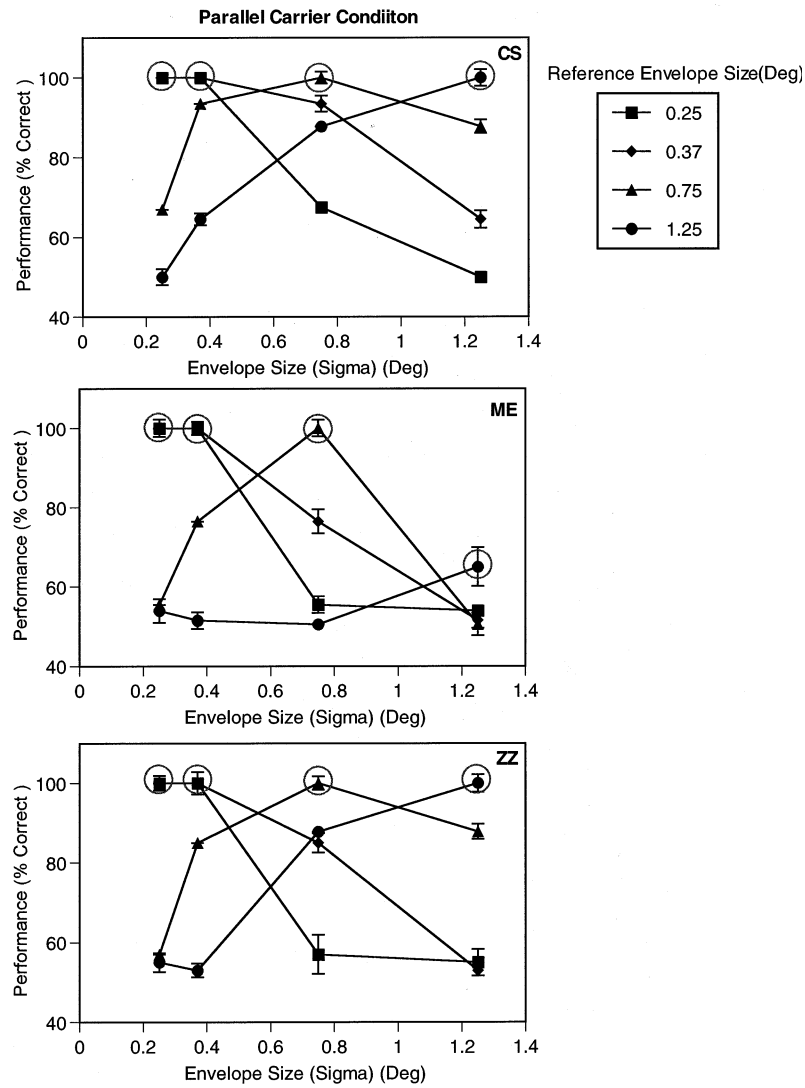

Fig. 4. Results for the small disparity- transient stimuli in Experiment 1. Percent-correct response for a small 0.5° disparity stimuli presented for 140 ms, is plotted against variable envelope size (σ). Four different σ s were paired dichoptically with variable σs shown along the abcissa. The results for parallel and orthogonal carrier stimuli are shown in (a) and (b), respectively. Performance was highest for both parallel and orthogonal orientations when the Gabors were equal in size. Performance declined as envelope size increased and was near chance level for all orthogonal stimulus pairs containing large envelopes (1.25°). Circled symbols represent matched stimulus sizes presented to the two eyes.

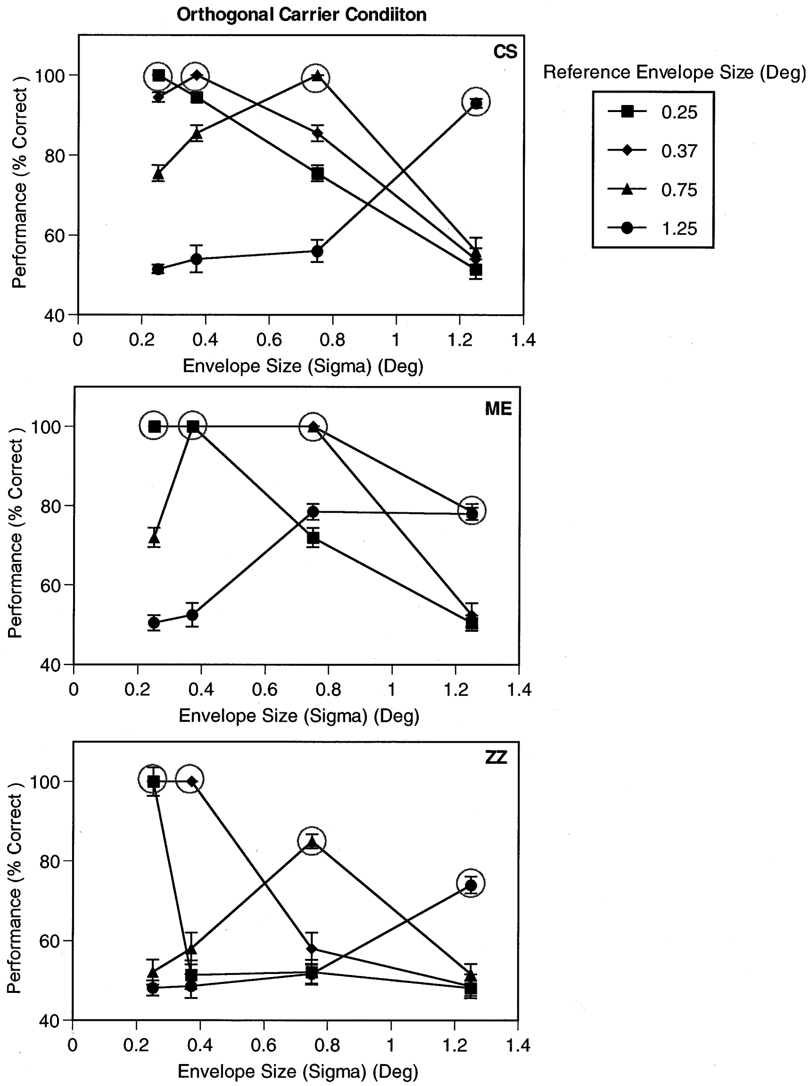

Fig. 4. (*Continued*)

3. Experiment 2: envelope tuning at large disparities

The present experiment investigated envelope tuning of the transient system at large (highly diplopic) disparities. The sustained system was not tested because it does not operate at these disparities (Ogle, 1952).

3.1. Stimuli and procedure

The stimuli and procedures were the same as used in Experiment 1 except that a larger disparity (5°) and a larger range of reference envelope sizes were used. Different envelope-size ranges were used for the three observers because ME exhibited poor performance with very large envelopes. For observers ZZ and CS, reference sizes of 0.25°, 0.75° and 2.5° were used, while for ME reference sizes of 0.2°, 0.6° and 2° were used. Similar to the quantitative-stereo system described by Ogle (1952), the sustained system does not operate at this large disparity. Accordingly, we only used the short-duration condition, to stimulate the transient system.

3.2. Results

The results for the three observers are shown in Fig. 5. Percent-correct is plotted against the variable envelope size (σ) of the Gabors. Different symbols represent the values of the reference sizes that were paired dichoptially with the stimulus size on the abscissa. The basic pattern of results is substantially the same for all observers. Transient stereo performance was very similar with parallel and orthogonal orientation carriers, suggesting that performance was determined by envelope size, independent of the carrier orientation. Performance was best with matched-size envelopes and remained good over a broader range of size differences than it did for the small-disparity condition shown in

Fig. 4. For two of the observers, ZZ and CS, performance with the largest envelope size (2.5°) was above chance until the size differences were greater than 3 octaves. Thus, it appears that the bandwidth for envelope-size tuning of the transient-stereo system increases with disparity amplitude. This increase can be attributed to better performance with large envelopes subtending large disparities, compared to small disparities. Note that while observer ME had narrower bandwidth tuning with the largest Gabor, his transient-stereo performance with matched large Gabors was better than that obtained with the small-disparity stimulus (Fig. 4). Also note that at the 5° disparity, all stimuli appeared diplopic and none of them underwent binocular suppression or rivalry. Thus, it is possible that the improvement in transient-stereo performance with large envelopes could be attributed to a reduction in binocular inhibition with increasing disparity. However, it is unlikely that this explanation could totally account for the present results because it does not explain why performance is better with large matched-sized envelopes than with dichoptically mixed small and large envelope sizes.

4. Experiment 3: contrast tuning

We have previously shown that transient-stereo performance with different spatial-frequency carriers can be improved by varying the relative contrasts of the two

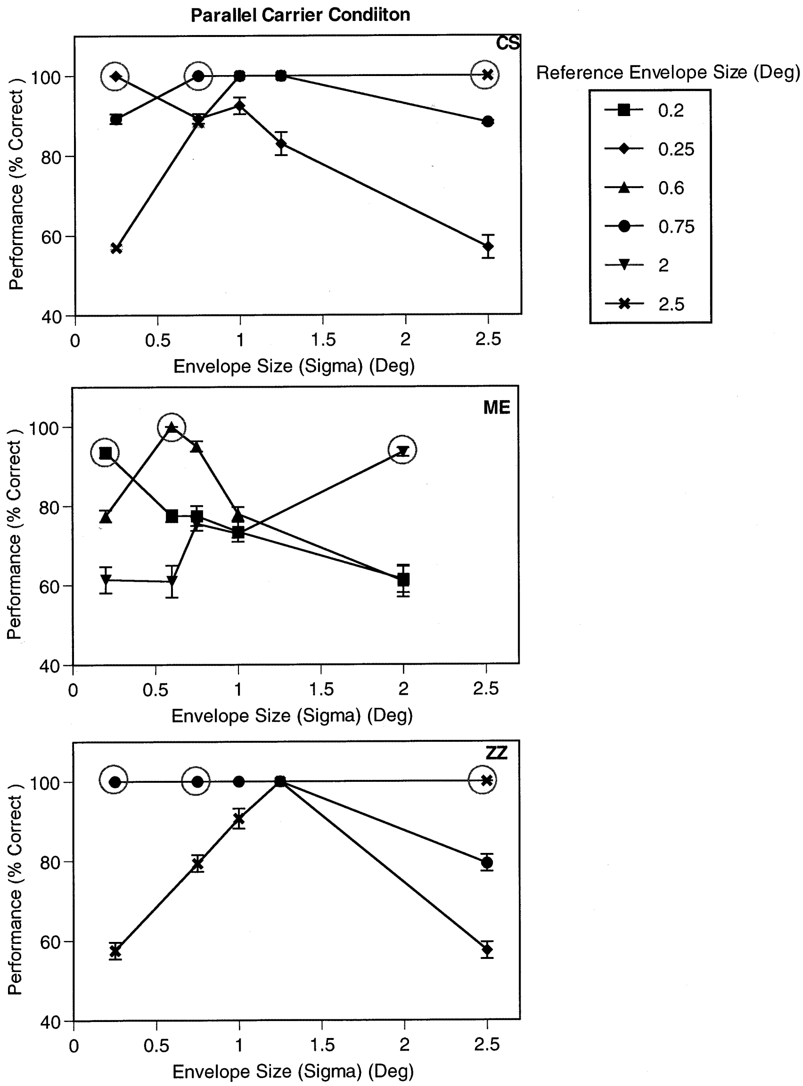

Fig. 5. Results for the large-disparity transient stimuli in Experiment 2. Percent-correct response for large 5° disparity stimuli presented for 140 ms, is plotted against variable envelope size (σ). Five different σs were paired dichoptically with variable σs shown along the abscissa. The results for parallel and orthogonal carrier stimuli are shown in (a) and (b), respectively. Performance was highest when the Gabors were equal in size for both parallel and orthogonal orientations and it remained high over a broader range of size differences (3 octaves) than it did for small disparity condition shown in Fig. 4. Circled symbols represent matched stimulus sizes presented to the two eyes.

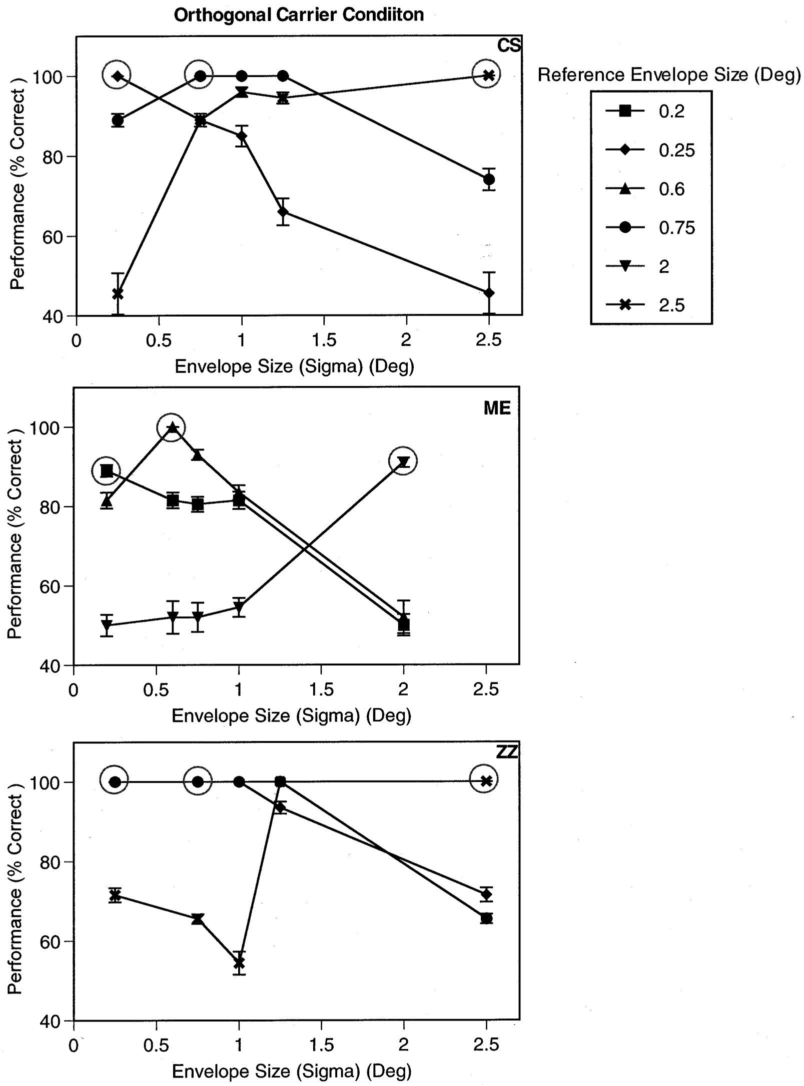

Fig. 5. (*Continued*)

eyes' stimuli (Schor et al., 1998). Such a finding is consistent with the model proposed by Kontsevich and Tyler (1994). In this model, the two ocular-based signals interact in an inhibitory manner prior to binocular combination. The outcome of this interaction is that the subsequent binocular activity will be lowered if the two ocular-based signals have different strengths. Because the activity in each ocular channel can be altered by varying stimulus parameters to which the system is tuned, reduced activity produced by a non-optimal spatial frequency could be increased by adjusting the relative contrast of the two retinal images. Specifically, stereo performance was improved by reducing the contrast of the Gabor with the lower carrier frequency to which the stereo system has greater sensitivity (Kontsevich & Tyler, 1994; Schor & Heckman, 1989; Schor et al., 1998). This experiment investigated whether varying the contrast between different sized Gabors presented to the two eyes could improve transient-stereo performance.

4.1. Stimulus and procedure

The stimulus was a dichoptic pair of a small envelope ($\sigma = 0.25°$) with a large envelope ($\sigma = 2.5°$ for CS and ZZ and 2.0° for ME) subtending a 5° disparity. Contrast of the small envelope was fixed at 100% while the contrast of the larger envelope varied from 0 to 100%.

4.2. Results

Results are shown for parallel and orthogonal carrier orientations in Fig. 6. Percent correct is plotted against the contrast of the large Gabor ($\sigma = 2.5°$ for CS & ZZ and 2.0° for ME). The 100% contrast point on the abscissa represents the condition in which the small and large Gabor had the same contrast. The basic pattern of results is the same for all three subjects. Two of the three observers (CS and ZZ) showed strong contrast tuning. Optimal performance with unmatched sizes with either parallel or orthogonal orientations was obtained when the contrast of the large Gabor was reduced to 5% or 10%. Reducing the contrast of the larger Gabor improved transient-stereo performance from near chance (48–58%) to 85–95%. The third observer (ME) showed weaker contrast tuning with unequal-size Gabors, even though he has previously shown strong contrast tuning with equal-size Gabors that have unequal carrier orientations and spatial frequencies (Schor et al., 1998). His contrast tuning improved when tested with a σ pairing of 1.5° and 0.2°. We also reversed this procedure and fixed the contrast of the large Gabor at 100% while the contrast of the smaller Gabor was varied and found no improvement in performance above the chance level.

Fig. 7 is a plot of the amplitude spectrum and spatial distributions (inset) of several full-wave rectified Gabor patches whose σ s differ over a 3-octave range. Note that in calculating the amplitude spectrum of the rectified Gabor, its mean luminance was normalized to zero. This was done because the visual system is concerned with deviations in luminance from mean luminance, and it thus treats any luminance below the mean as a negative value. The amplitude spectra of the rectified images are composed of a low-pass zone and several band-pass zones that are associated with the Gaussian envelope and the full-wave rectified carrier, respectively. Because the second filtering stage in the second-order system is thought to be tuned at a lower spatial frequency than the first (Sutter et al., 1995), we

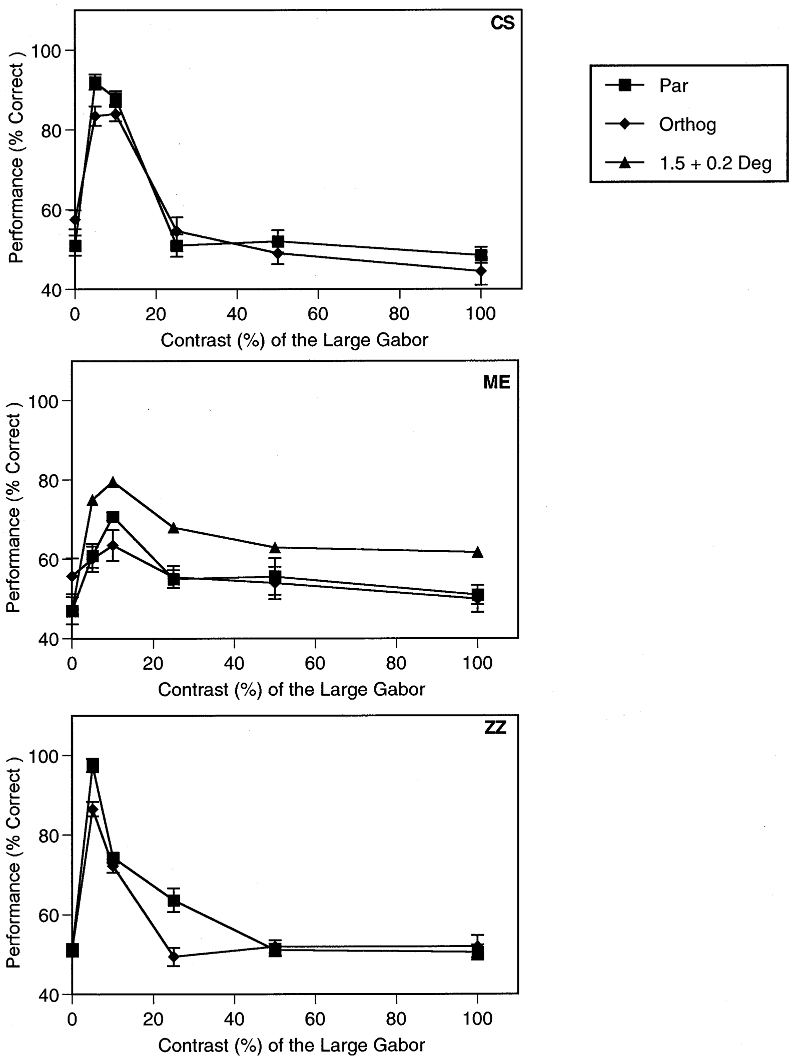

Fig. 6. Results for contrast tuning in Experiment 3. Percent-correct response for large 5° disparity stimuli presented for 140 ms, is plotted against contrast of a large Gabor stimulus ($\sigma = 2.5°$ for CS & ZZ and 2.0° for ME) which was paired with a small ($\sigma = 0.25°$) Gabor set at 100% contrast. The 100% contrast point on the abscissa represents the condition in which the small and large Gabors had the same contrast. Both parallel (Par) and orthogonal (Orthog) carrier orientations were tested. Optimal performance for two subjects (CS and ZZ) was obtained when the contrast of the large Gabor was reduced to 5 or 10%. Subject ME showed weaker tuning. ME was also tested with a σ pairing of 1.5° and 0.2°. The result suggests that contrast tuning can narrow the bandwidth of envelope-size tuning.

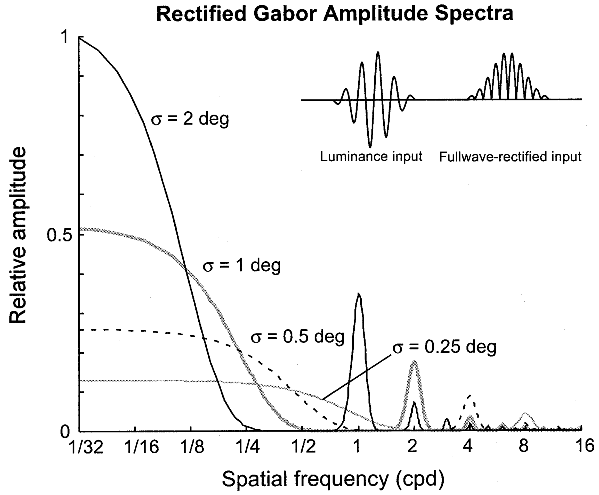

Fig. 7. Amplitude frequency spectra of three rectified Gabor patches (inset). Each spectrum contains a low-pass component that represents the Gaussian envelope, and several band-pass components that represent the rectified carrier. We assume that the second-order process is only tuned to the low-pass frequency components of the Gaussian envelope (Sutter et al., 1995). Amplitudes of the low-frequency components increase proportionally with envelope size (σ).

only consider binocular interactions in the low-frequency range corresponding to the Gaussian envelope. Second-order stereo is assumed to match information in the overlapping spectral regions corresponding to the extracted envelopes. In the region of overlap, the amplitude of the low-frequency component increases proportionally with σ. Following the logic of the Kontsevich and Tyler model (Kontsevich & Tyler, 1994), stereo performance would be improved by reducing the contrast of the larger Gabor patch presented to one eye. This would reduce the difference in amplitude with a smaller Gabor presented to the other eye. Our observations confirm this prediction and they suggest that binocular matches are made in transient stereopsis between aspects of the Gabor patch that are not represented in the luminance distribution. Matches are made after the output of some non-linear process, such as full-wave rectification.

5. General discussion

Several general conclusions can be drawn from our experiments. Our first experiment demonstrated that second-order (extracted-envelope) information could be utilized by sustained stereopsis with small-disparity stimuli. When tested with orthogonal Gabor patches, sustained stereopsis was possible as long as the contrast envelopes were not large. The failure of the larger orthogonal matched-size envelope to be effective in stimulating sustained stereopsis may have resulted from binocular-inhibition processes, such as rivalry suppression. Indeed, the briefer transient stimulus, for which rivalry is weaker (Hering, 1879; Breese, 1899), was very effective at stimulating transient stereopsis with the same large size-matched orthogonal Gabor patches.

The first experiment also demonstrated that the transient stereo system, stimulated by both orthogonal and parallel orientations, responds very well to the small disparity (0.5°) that was within Panum's fusional area (Schor, Wood, & Ogawa, 1984b). This confirms the observations by Liu, Tyler, Schor, and Ramachandran (1992) and Pope et al. (1999) who measured stereo thresholds with non-fusable targets that were similar to those used in this study. The present study extends those early observations by illustrating the broad bandwidth of the envelope-size tuning (2–3 octaves from the reference size). An equal bandwidth of 2 octaves was found for the sustained- and transient-stereo systems when stimulated with Gabors containing parallel carrier orientation that subtended a small disparity. Bandwidth was reduced for size tuning of the sustained response to orthogonal orientations presented in large envelopes and it was broader for sustained responses to orthogonal carriers contained in small envelopes.

Wilcox and Hess (1996) were unable to elicit depth percepts with small orthogonal noise patches subtending any disparity magnitude (1.89-octave bandwidth with a center frequency of 1.5 c/deg and $\sigma = 0.22°$). The broad bandwidth of their stimulus is comparable to that of the orthogonal Gabor used by Liu et al. (2 cycles of the cosine carrier were visible in the envelope). The main differences between the studies were the low contrast (8 dB above detection threshold) and random phase of the noise carrier used by Wilcox and Hess (1996). We have re-evaluated their noise stimulus and were able to demonstrate robust transient stereopsis with the same broad-band orthogonal-noise stimulus that Wilcox and Hess (1996) described in their paper, presented at 25% contrast subtending either 0.5° or 5.0° disparity. It is possible that the absence of stereopsis with this stimulus reported in their study is attributed to its low contrast level of 8 dB above threshold.

Our second experiment demonstrated that bandwidth for envelope-size tuning of transient stereopsis increased with disparity magnitude (over 3 octaves from the reference size) and was substantially independent of orientation differences between the carriers. The increased bandwidth is mainly the result of improved performance with large envelopes subtending large disparities. This result is consistent with the size-disparity correlation reported by Wilcox and Hess

(1995) for Dmax and envelope size. The size-disparity correlation also occurs in the first-order, or luminance domain for stereo threshold, where stereo threshold increases as spatial frequency decreases below 2.5 cpd (Schor & Wood, 1983; Schor et al., 1984a; Hess & Wilcox, 1994). The size-disparity correlation for both luminance and contrast components of the stimulus indicates that first- and second-order mechanisms use similar disparity processing strategies.

The third experiment demonstrated that varying the relative contrast of the unequal-size dichoptic Gabors could improve stereo performance. Reducing the contrast of the larger Gabor improved transient-stereo performance from near chance (48–58%) to 85–95%. A similar demonstration has been made for spatial-frequency tuning of the Gabor carrier. Schor et al. (1998) observed that reduced performance with dichoptic Gabors with unequal carrier frequencies could be improved by reducing the contrast of the lower-frequency carrier. Thus, the bandwidths for envelope-size tuning and carrier spatial-frequency tuning are effectively much broader than indicated in Experiment 2.

The observed tuning to envelope size, while broad, is tighter than that observed for carrier spatial frequency (Schor et al., 1998), carrier orientation (Edwards et al., 1999), and contrast polarity (Pope et al., 1999) of the stimulus. Thus, it would appear that envelope size and, to a greater extent, temporal synchrony of the dichoptic stimuli (Cogan et al., 1995) are the primary means for selecting matched binocular inputs for transient stereopsis.

Envelope size and carrier information are used together to make binocular matches using a coarse-to-fine disparity strategy. Second-order information from the envelope provides coarse information to guide matches of small disparities in the carrier by the fine system (Wilcox & Hess, 1997). This is not a function reserved exclusively for second-order stimuli because coarse first-order luminance information also guides disparity matches at finer scales (Wilson, Blake, & Halpern, 1991a). This coarse-to-fine strategy utilizing contrast and luminance information is effective because spatial information represented by contrast and luminance is usually highly correlated in images formed in natural environments. Transient stereopsis appears to rely more heavily on second order information than does sustained stereopsis (Pope et al., 1999) however the current study illustrates the use of second-order information by the sustained system.

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