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Vision Research 39 (1999) 4010–4017

Vision Research

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Extraction of depth from opposite-contrast stimuli: transient system can, sustained system can't

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Received 3 December 1998; received in revised form 31 March 1999

Abstract

The ability of observers to extract depth from opposite luminance-contrast-polarity stimuli was investigated. The stimuli consisted of two dichoptic-pairs of Gaussians, with one of the Gaussians in each pair having a positive contrast-polarity and the other a negative contrast-polarity. Stimulus durations ranging from 0.2 to 4 s were used. This range of durations was employed to reveal stereo mechanisms that were preferentially sensitive to transient or sustained stimuli. Stimuli were presented in a raised-cosine temporal envelope. Performance with stimuli of the same contrast-polarity was also tested. Observers could easily perceive depth with the same-polarity stimuli, at both long and short durations. Depth could be perceived with low-contrast opposite-polarity stimuli only at short durations. However, depth could be perceived with long-duration stimuli presented within a raised cosine temporal-envelope if a high contrast was used. Depth could also be perceived with low-contrast long-duration stimuli if they were presented within a rectangular temporal-envelope. These findings suggest there are separate sustained and transient mechanisms for stereopsis and that the transient-stereoscopic system can extract depth from opposite-contrast stereograms while the sustained system cannot. Further, it is likely that depth perception with opposite-contrast stereograms found in many previous studies was mediated by the transient-stereopsis system. © 1999 Elsevier Science Ltd. All rights reserved.

Keywords: Contrast; Polarity; Stereopsis; Transient; First-order; Second-order

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1. Introduction

Helmholtz (1925) observed that it is possible to extract the correct depth from an opposite luminance-contrast stereogram. The stereogram he used consisted of a line drawing of a polyhedron, in which one eye was presented with a black figure on a white background and the other with a white figure on a black background. To account for this finding, Helmholtz proposed that the stereoscopic system matched luminance contours, and that in this matching, the polarity sign of the contour was not a factor. Since Helmholtz's demonstration, the question of whether stereopsis is possible with opposite-polarity stimuli has been debated (e.g. Treisman, 1962; Kaufman & Pitblado, 1969; Anstis & Rogers, 1975; Cogan, Konstevich, Lomakin, Halpern & Blake, 1995). For example, it has been clearly demonstrated that opposite-polarity stereopsis is not possible with random-dot stereograms (Julesz, 1971; Stuart, Edwards & Cook, 1992). Julesz attributed the difference in the results between figural and random-dot stereograms to be due to the greater 'complexity' of spatial contours in the random-dot stereogram. Such a notion was supported by the study of Cogan, Lomakin and Rossi (1993).

A number of the researchers, whose own findings are consistent with those of Helmholtz, reject his view that stereopsis is due to the matching of opposite-polarity contours. Instead, they proposed that like-polarity contours are actually being matched. With narrow, figural stereograms, it would be possible to align the like polarity edges by perceptually introducing a small spatial offset to one of the images (Treisman, 1962). With broader stimuli, and stimuli that do not have continuous like-polarity luminance contours (e.g. random-dot stereograms) the matching of like-polarity contours could still be possible since the visual system represents any contour with 'contours' of both 'polarities'. This dual representation is due to the spatial filtering of the

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PII: S0042-6989(99)00106-6

visual system. Spatial filtering by receptive fields with antagonistic centres and surrounds represent a luminance contour of one polarity within the visual system as two contours. One contour has the same polarity as the original contour and a spatially-adjacent contour has the opposite sign (Kaufman & Pitblado, 1969; Anstis & Rogers, 1975; Cogan et al., 1995). Mach Bands are an example of such a representation (Mach, 1866). Thus stereopsis with opposite-polarity contours could be due to the binocular matching of these spatially offset like-polarity representations. However Cogan et al. (1995) have shown that such an explanation cannot account for all instances of opposite-polarity stereopsis.

In considering this issue, it may be important to keep in mind that stereoscopic-depth perception appears to be mediated by at least two mechanisms. One system requires briefly presented (transient) stimuli, otherwise the percept of depth fades (Ogle, 1952; Westheimer & Tanzman, 1956) and it can process highly-diplopic images (up to 10° in disparity). The other system requires longer (sustained) stimulus durations, being able to generate a sustained sense of depth, and mainly processes dichoptic stimuli that are fused (Ogle, 1952). Ogle labeled these systems qualitative and quantitative, respectively, due to his observation that the perceived depth mediated by the quantitative system varies with the magnitude of the disparity while the qualitative system merely gives the sign of the depth. There are, however, some notable exceptions to Ogle's classification of these two systems, specifically with respect to the disparity range over which they operate and the perceived depth-magnitude they generate. In a number of pilot studies, we have observed that the qualitative system can process small disparities that are within Panum's fusional area. That is, while the quantitative system is limited to processing small disparities, the qualitative system can process both small and highly diplopic disparities. We have also found that the magnitude of the perceived depth mediated by the 'qualitative' system can be varied (by changing the spatial-frequency content of the stimuli) though this effect may be monocular in nature. Richards and Kaye (1974) also observed quantitative variations in stereo depth stimulated with brief duration disparities up to 4° in magnitude. Based upon these observations, it would appear that the defining differences between these two systems are their respective temporal sensitivities and upper limits ($D_{\max}$). Accordingly, we describe them in a way analogous to the description of the transient and sustained components of the disparity-vergence system (Jones, 1980).

We have previously shown that the transient-stereoscopic system is less tightly tuned to various physical parameters of the stimulus than is the sustained system. Specifically, we have shown that the transient system exhibits dichoptic broadband tuning to spatial frequency (Schor, Edwards & Pope, 1998) and orientation (Edwards, Pope & Schor, 1999) as opposed to the sustained systems more narrowband tuning to these parameters (e.g. Mitch & O'Hagan, 1972; Schor, Wood & Ogawa, 1984). The main aim of the present paper is to determine whether the transient system shows less selectivity to luminance polarity than does the sustained system. Specifically, the aim is to determine whether we can distinguish between a transient and sustained stereo system on the basis of depth extraction from opposite-polarity stereograms. In an attempt to selectively drive the transient or sustained systems, we varied both the temporal duration and temporal-envelope shape of the disparate stimuli. We observed that stereo depth could be perceived with dichoptic opposite contrast stimuli when they were presented at short but not long durations. These and other observations support our notion of distinct transient and sustained stereo-systems.

1.1. Method

1.1.1. Observers

Four observers were used: the three authors and one observer who was naive with respect to the aims of the study. All had either normal or corrected to normal visual acuity, normal stereopsis (as measured by a Randot Stereotest™) and no history of any binocular visual disorders.

1.1.2. Stimuli and procedure

Stimuli used were Gaussians. The observer first maintained fixation on a pair of crosses and vertical nonius lines. Once fixation had been established, with the nonius lines perceptually aligned, the observer initiated the presentation of the test stimulus. The test stimuli replaced the nonius lines and consisted of two pairs of dichoptic Gaussians, with the centers of one pair presented 2.2° above and the other 2.2° below the former center location of the fixation point. One of these pairs was presented at a crossed and the other at an uncrossed horizontal disparity relative to the depth defined by the fixation point. Two contrast conditions were used. A same-polarity condition in which all of the Gaussians had the same (positive) luminance polarity and an opposite-polarity condition in which opposite contrasts were dichoptically paired.

Both the standard deviation and the disparity of the Gaussians were 0.5°. This combination of Gaussian standard deviation and disparity meant that observers would perceive reverse depth with the opposite-contrast condition if they matched the like-polarity borders of the Gaussians (Cogan et al., 1995). Matching the opposite-polarity midpoints of the Gaussians would result in perception of the correct depth direction (see Fig. 1). Since two depth precepts were possible, no feedback was given to the observers as to the correctness of their response.

The presence of paired crossed and uncrossed disparities in the same insured that observers with a transient-depth bias in either direction (Richards, 1973) would be sensitive to at least one of the two dichoptic pairs of stimuli. In addition, observers could not use vergence eye movements elicited by the mixed disparity stimulus to determine the sign. The observers task was to indicate which Gaussian pair (upper or lower) was at the crossed disparity.

In an attempt to find stimulus conditions that would selectively activate either the transient or sustained systems, a range of stimulus durations and contrasts were used. For all durations, a temporal raised-cosine envelope was employed. The use of such a temporal envelope meant that increasing the stimulus duration resulted in a reduction in the stimulus energy at high temporal frequencies, and an increase in the amount of temporal energy at low (around 0 Hz) frequencies. To stress this point, increasing the stimulus duration did not necessarily add energy, or make the stimulus 'easier to see', but rather, it selectively increased low temporal frequency components at the expense of the high-temporal-frequency information (see Fig. 2). Thus, a very brief stimulus would likely drive the transient system, to the exclusion of the sustained system. Increasing the stimulus duration would decrease the likelihood that the stimulus would activate the transient system and increase the likelihood that it would activate the sustained system.

Two of the observers (ME & CS) were tested on a range of contrast and temporal-duration combinations. Contrasts used were 40, 60, 80 and 100% and temporal durations were 0.2, 0.5, 1, 2 and 4 s. Based upon the results obtained for these conditions, the remaining observers (EG & DP) were tested with the two extreme stimulus durations (0.2 and 4 s) at the lowest contrast for which they could reliably extract depth from the opposite-contrast condition at the shortest duration. This contrast level was 60% for EG and 40% for DP. The mean luminance of the display was 25 cd/m^2. In both conditions, the fixation point was continuously displayed. The viewing distance was 1.0 m. Stimuli were presented in blocks of 20 and each data point reported represents the mean of ten blocks.

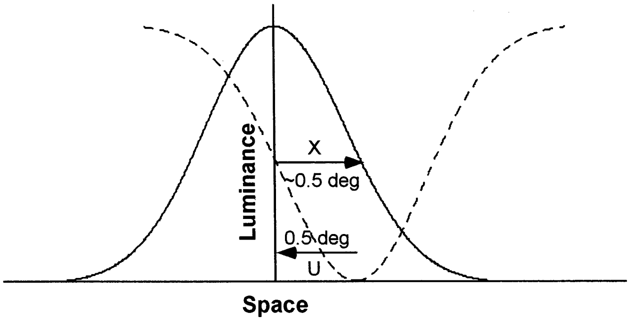

Fig. 1. Disparities resulting from various possible binocular matches. The solid Gaussian represents the stimulus presented to the left eye and the dashed Gaussian the stimulus presented to the right eye. The arrows represent two possible binocular matches; the bottom arrow designates the alignment of the midpoints of the Gaussians, and the top arrow designates the alignment of the same-signed luminance contours. For the case shown, midpoint matches would produce an uncrossed (U) disparity of 0.5°, while same-sign luminance contour matches would produce a crossed (X) disparity of approximately 0.5°.

1.1.3. Apparatus

Stimuli were generated using a Cambridge Research Systems VSG 2/3 graphics card in a host Pentium computer and displayed on a Vision Research Graphics monitor. The dichoptic half-images were selectively presented to each eye via the use of Vision Research Graphics ferro-electric shutters. The frame rate of the monitor was 120 Hz so that the effective frame rate to each eye was 60 Hz. The observer initiated each trial and responded via a button box. A chin rest was used to stabilise the observer's head. A custom Vision Research Graphics monitor, which has a P41 rapid-decay phosphor, was used. The use of the rapid-decay phosphor ensured that there was no bleed through of the images between the two eyes.

1.2. Results and discussion

The results are shown in Figs. 3 and 4. Figure 3 shows the results for the complete set of contrast and duration conditions for observers ME and CS. Performance (% of responses that were correct) is plotted against the stimulus duration for the two conditions (opposite-polarity (OPol) and same-polarity (SPol)) at the various stimulus contrast levels (40–100%). Error bars represent plus and minus one standard error of the mean. The basic pattern of results is the same for both observers. For the same-polarity condition, performance either remained constant at 100% (CS) or improved to the 100% level (ME) as stimulus duration was increased. Variation in contrast had no effect on measured performance. This lack of performance variations due to a ceiling effect, i.e. performance at the lowest contrast level was already at 100% and could not be improved upon. For the opposite-polarity condition, performance levels decreased as the stimulus duration was increased and there was a marked effect of reducing contrast.

The dependence of performance for the opposite-polarity condition upon stimulus duration is further supported by the results for the other two observers (DP & EG) at the two extreme stimulus durations (0.2 and 4 s). In Fig. 4, performance is plotted for the four conditions: same polarity at short-SPol (0.2) and long-SPol (4) durations, and opposite polarity at short-OPol (0.2)

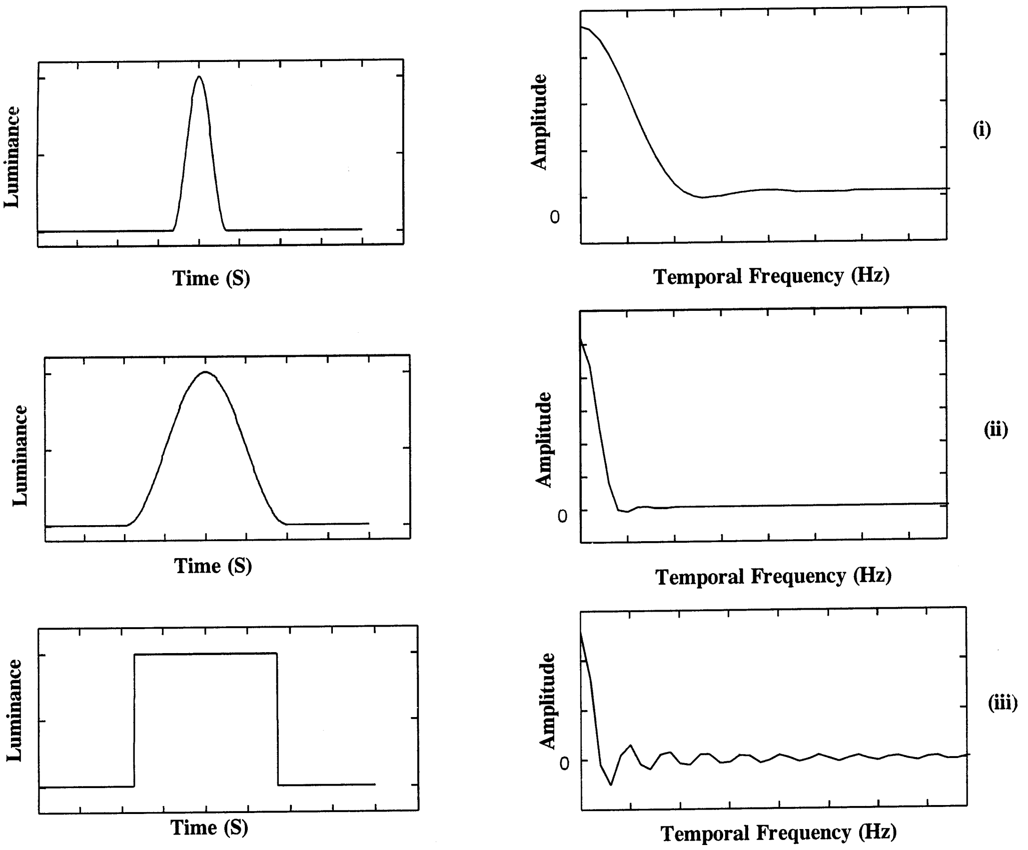

Fig. 2. Temporal envelopes of raised cosine and rectangular functions and their respective temporal-frequency energy profiles. Shown are two cosine envelopes (i & ii, ii is three times longer than i) and a rectangular envelope (used in experiment 2—iii has the same duration as ii). For the cosine envelope, the zero-energy crossing-point (i.e. where the temporal energy goes from being positive to negative) occurs at twice the fundamental temporal frequency of the cosine, where the fundamental equals the reciprocal of the stimulus duration. The cosine durations (periods) used were 0.2, 0.5, 1, 2 and 4 s: There is a factor of 20 difference between the lowest and highest values. These periods correspond to temporal frequencies of 5, 2, 1, 0.5 and 0.25 Hz, respectively, and hence zero-energy crossing-points of 10, 4, 2, 1 and 0.5 Hz. Thus, increasing the temporal duration of the stimulus from 0.2 to 4 s led to a substantial decrease in high-frequency energy. For the rectangular envelope, the first zero-energy crossing-point occurs at one over its fundamental temporal period. A 4 s duration has its zero-energy crossing-point at 0.25 Hz. Note that this is at half the value of that for the same-duration cosine envelope, however the temporal-energy profile produced by the rectangular envelope (sinc function) has more high-frequency energy in its cyclic lobes. Note, also, that a negative temporal energy corresponds to a phase shift of 180°.

and long-OPol (4) durations. Results for these conditions are given for the two new observers and for the two other observers (ME & CS) whose complete set of results were given in Fig. 3. The basic pattern of results is the same for all observers. For both of the same-polarity conditions, performance is high. This is especially true for the long-duration (4 s) condition for which all observers achieved 100% correct performance. However, for the opposite-polarity conditions, good performance was obtained only for the short-duration (0.2 s) condition. Performance for the long-duration condition was at chance levels. Note that this chance-level performance indicates that reverse depth was not being perceived. If reverse-depth was being perceived, performance levels would have been significantly below the 50%, approaching 0% for perfect reverse-depth perception. This result indicates that stereo with reversed contrast stimuli does not the result from a disparity match of like contrast gradients within the stimulus (see Fig. 1).

The present results are that opposite-polarity stereograms can be perceived at short-durations, and that same-polarity stereograms can be perceived with both long and short durations. Because the short-duration stimuli drove the transient system while the longer-duration stimuli preferentially drove the sustained system, the present results indicate that while the transient system can extract depth from opposite-polarity stereograms, the sustained system cannot. That the long-duration stimuli where actually driving a sustained system was confirmed by the results for the same-polarity condition. For that condition, not only was depth perception particularly easy, but the perception of depth endured for the duration of the stimulus, i.e. the perception of depth was sustained in nature.

While the present results are compatible with those of earlier studies that found depth could be perceived with briefly-presented opposite-contrast stimuli (Cogan et al., 1995) are they inconsistent with studies that found opposite-contrast depth perception with long-duration stimuli? That the present results are not necessarily inconsistent with those earlier findings resides in the fact that the temporal-frequency energy of a stimulus is not determined exclusively by its duration. High temporal-frequency energy can occur in both short and long duration stimuli. For example, a long duration stimulus presented within a raised cosine temporal envelope would contain high-frequency energy if its contrast was high. Also, a stimulus presented within a long duration rectangular temporal envelope would contain high-frequency energy (at the stimulus onset and offset) at high and low contrast levels. Refer to Fig. 2. That is, the temporal-frequency content of a stimulus depends upon the temporal duration, temporal-envelope shape and contrast level. Thus performance should also depend upon these factors. The results for the long-duration raised-cosine temporal envelope of observers ME and CS at high contrast levels (Fig. 3) support this notion. To further test this idea, observers DP and EG were tested with long duration stimuli (4 s) presented in two different temporal-envelope and contrast combinations. One was a high-contrast (100%) stimulus presented within a raised-cosine temporal-envelope (HC-cosine) and the other was a low-contrast (corresponding to the contrast used for the observer in experiment 1, Fig. 4) stimulus presented within a rectangular temporal-envelope (LC-rect). The rectangular window introduces a broader range of high temporal frequencies than does the Gaussian window—see Fig. 2. The results for the two observers are presented in Fig. 5. For purposes of comparison, also shown is each observers performance for the low-contrast Gaussian presented within a temporal cosine envelope (LC-cosine) condition used in

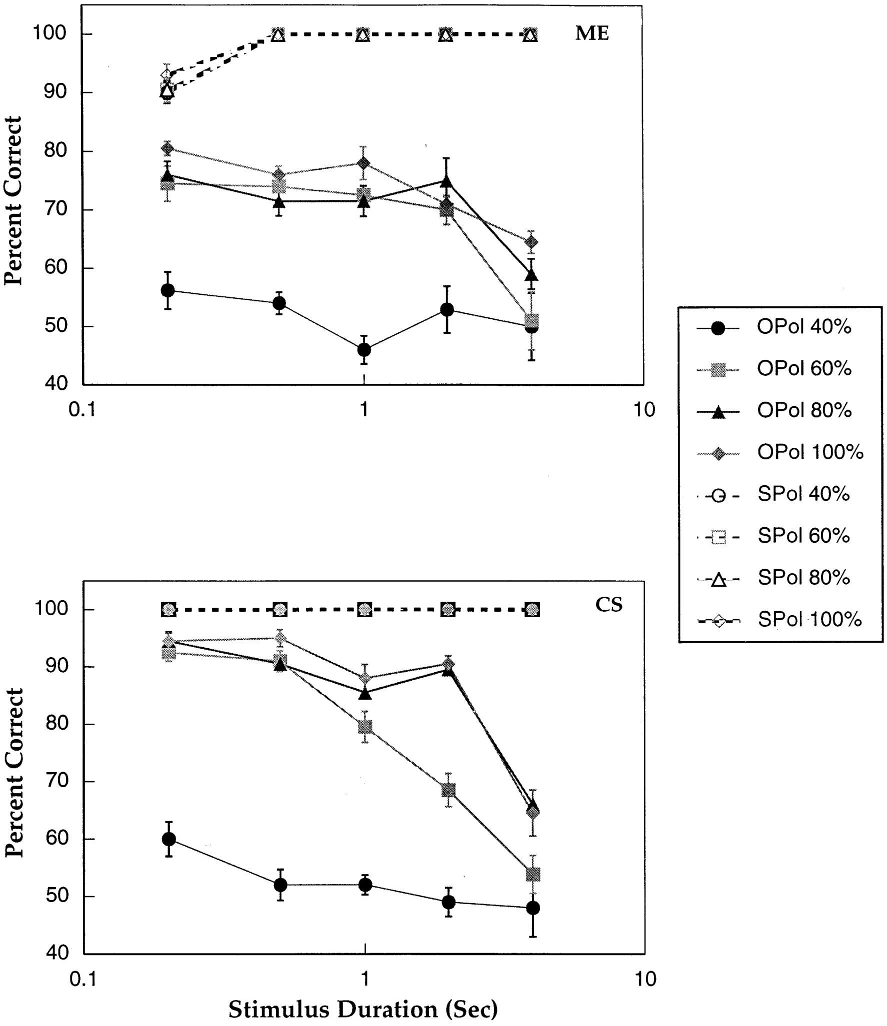

Fig. 3. Results for experiment 1. Performance (% correct responses) for the opposite-polarity (OPol) and same-polarity (SPol) conditions are plotted against stimulus duration for the four contrast conditions used (40, 60, 80 and 100%). Error bars represent plus and minus one standard error of the mean.

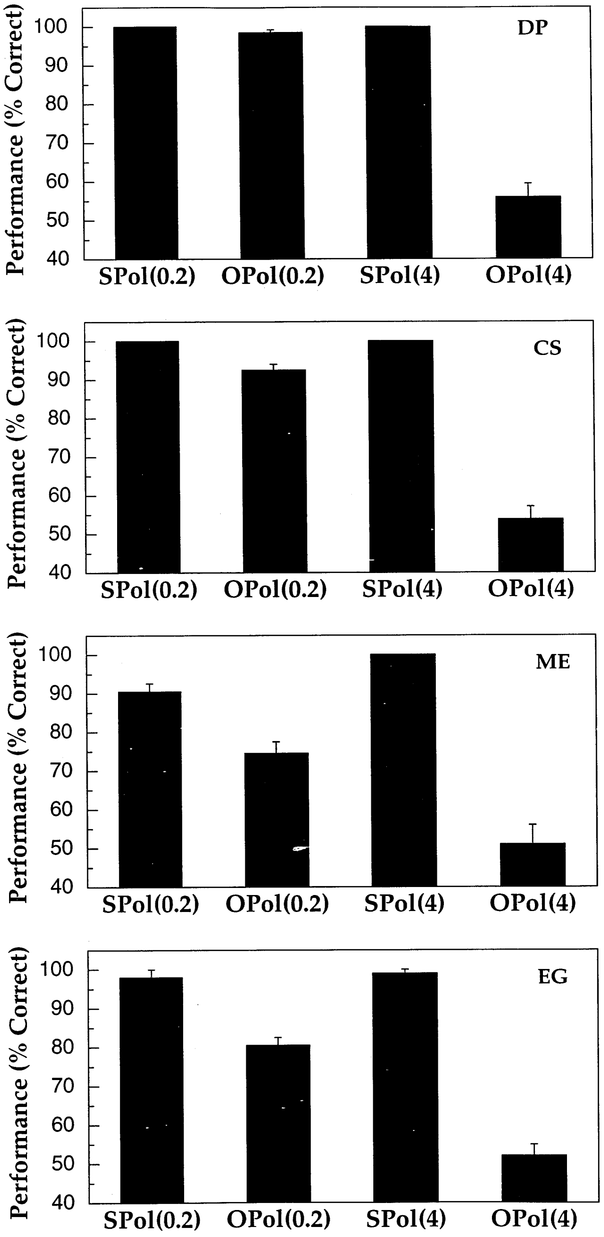

Fig. 4. Results for experiment 1. For each observer, performance for the four conditions is shown. The conditions are: short-duration (0.2s) same-polarity-SPol (0.2); short-duration opposite-polarity-OPol (0.2); long-duration (4 s) same-polarity-SPol (4) and long-duration opposite-polarity-OPol (4). All observers showed good performance on the two same-polarity conditions while they exhibited above chance performance only with the short-duration stimuli on the opposite-polarity conditions.

experiment 1. The pattern of results is the same for both observers. While performance for the long-duration condition used in experiment 1 (LC-cosine) was at chance level, performance for the two new long-duration conditions (HC-cosine & LC-rect) are well above chance. Thus, as was suggested by the pattern of results in Fig. 3, short duration per se, does not enable stereo-depth perception with opposite-contrast stimuli; rather, the temporal shape and contrast of the stimulus determine the necessary high frequency temporal energy.

2. General discussion

Our studies with opposite-contrast stimuli demonstrate that stereo depth could be perceived: (i) with short but not long duration stimuli presented within a raised cosine temporal envelope at a low contrast; (ii) with long-duration stimuli presented within a raised cosine temporal envelope if a high contrast was used; and (iii) with long-duration stimuli presented within a rectangular temporal at a low contrast. These observations indicate that opposite-contrast stereograms can stimulate a transient but not a sustained stereoscopic system. Further, it is likely that the perception of depth with opposite-contrast stereograms reported in many previous studies was being mediated by a transient-stereopsis system.

The present findings have a number of implications for our claim of distinct transient- and sustained-stereoscopic systems. The finding that the ability of observers' to perceive depth from opposite-contrast stereograms was determined by the temporal-frequency composition of the stimulus supports the basic notion that two separate types of stereopsis can be categorized accord-

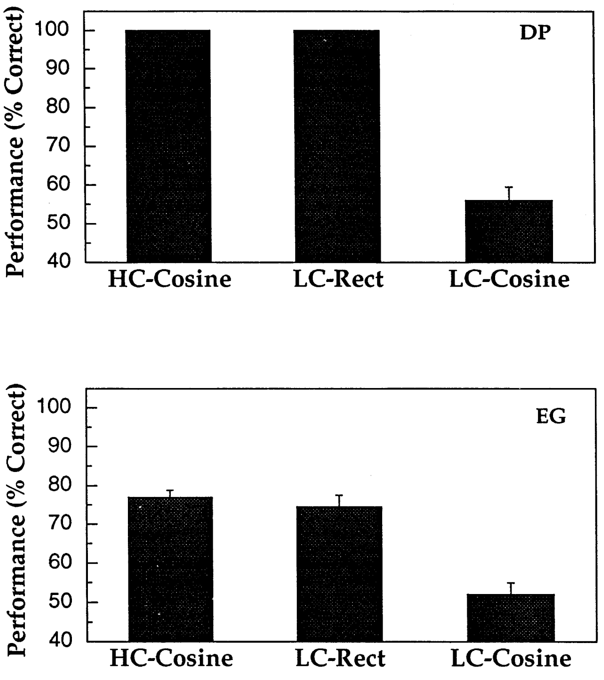

Fig. 5. Results for the two long-duration conditions used in experiment 2; high-contrast stimulus within a cosine temporal-envelope (HC-cosine) and a low-contrast-stimulus within a rectangular temporal-envelope (LC-rect). For purposes of comparison, results for the low-contrast cosine-envelope condition from experiment 1 are also shown. Both observers could extract stereo depth from the two conditions used in experiment 2.

ing to their respective temporal sensitivities. In relation to this issue, it is not valid to consider a critical temporal-duration as the defining difference between the transient and sustained systems. The critical duration for stimulating one system or the other will depend upon the contrast and the temporal envelope used (Figs. 2–4), i.e. upon the temporal energy within the stimulus. Thus instead of defining the two systems in terms of a critical stimulus-duration, a critical temporal-energy requirement might be more appropriate. There may even be a partial overlap of the temporal frequency ranges for the two systems. This notion is supported by the gradual decline in performance observed in Fig. 3. Given that the stimuli used in the present study contained a range of temporal frequencies (Fig. 2) these results do not allow us to precisely define the lower frequency limit for the transient system or the upper frequency limit for the sustained system. Furthermore, the marked variation in performance between the present observers questions the value of determining these limits, since they would have large individual variations. In relation to the defining spatial differences between the two stereo-systems, the present study shows that both systems can operate on disparities within Panum's area (0.5° disparity) however, the difference in their upper disparity limits remains an important distinction (Ogle, 1952). That is, while the transient system can process large disparities (up to 10°) the sustained system cannot (Westheimer & Tanzman, 1956).

The present results also allow us to draw some conclusions concerning the mechanisms underlying both transient and sustained stereopsis. A number of authors have demonstrated the existence of second-order stereo-processing system/s (Sato & Nishida, 1993; Hess & Wilcox, 1994; Wilcox & Hess 1996, 1997). While, at this stage, it is uncertain whether both the transient and sustained systems incorporate a second-order stage, our studies to date have indicated that the transient system does (Schor et al., 1998; Edwards et al., 1999). The ability of the transient system to extract depth with opposite-contrast stimuli indicates that the non-linear stage in the transient system is fullwave rectifying in nature. The failure of the sustained system to extract opposite-polarity depth with long duration stimuli indicates that, if the sustained system incorporates a second-order pathway, it would not implement fullwave rectification. Any non-linear stage in a putative second-order sustained pathway would have to be halfwave rectifying in nature.

Finally, how do we reconcile the present findings that stereo depth is stimulated with opposite-contrast stimuli at short durations with those observations of Cogan et al. (1993)? These authors found that stereo depth could not be perceived with briefly-presented (15 ms) opposite-contrast random-dot stereograms. When the spatial resolution and likely function of the transient system are considered, it becomes apparent that present findings are not applicable to random-dot stimuli. Our studies to date have indicated that the transient-stereo system has very coarse, low-pass spatial-tuning (Schor et al., 1998; Edwards et al., 1999). Coarse spatial tuning would make the transient system suitable for the initial detection of a disparity stimulus but not for detailed spatial-analysis of a complex depth stimulus (see also the discussion in Wilcox & Hess, 1997). Indeed, Cogan et al. (1993) found that observers could perceive the depth of a simple random-dot stereogram (i.e. one containing only a few dots) however, their performance decreased to chance level as the complexity (number of dots) of the stereogram increased (see also Ziegler & Hess, 1999). Spatially-complex stimuli, like random-dot stimuli, appear be processed exclusively by the sustained system, which, as demonstrated in the present study, cannot match opposite-contrast stimuli.

Acknowledgements

This project was supported by NEI grant EY08882.

References

Anstis, S. M., & Rogers, B. J. (1975). Illusory reversal of visual depth and movement during changes in contrast. *Vision Research*, *15*, 957–961.

Cogan, A. I., Lomakin, A. J., & Rossi, A. F. (1993). Depth in anticorrelated stereograms: effects of spatial density and interocular delay. *Vision Research*, *33*, 1959–1975.

Cogan, A. I., Konstevich, L. L., Lomakin, A. J., Halpern, D. L., & Blake, R. (1995). Binocular disparity processing with opposite-contrast stimuli. *Per ception*, *24*, 33–47.

Edwards, M., Pope, D. R., & Schor, C. M. (1999). Orientation tuning of the transient-stereopsis system. *Vision Research*, *39*, 2717–2727.

Helmholtz, H. V. (1925). *Treatise on physiological optics*. New York: Dover Press.

Hess, R. F., & Wilcox, L. M. (1994). Linear and non-linear filtering in stereopsis. *Vision Research*, *34*, 2431–2438.

Jones, R. (1980). Fusional vergence: sustained and transient components. *American Journal of Optometry and Physiological Optics*, *57*(9), 640–644.

Julesz, B. (1971). *Foundations of cyclopean perception*. Chicago: University of Chicago Press.

Kaufman, L., & Pitblado, C. B. (1969). Stereopsis with opposite contrast contours. *Perception and Psychophysics*, *6*, 10–12.

Mach, E., 1866. Uber die physiologische Wirkung raumlich vertheilter Lichtreize (Dritte Abhandlung). Sitzungsberichte der Ostereichischen Akademie de Wissenschaften, 54, 393–408. Trans. in F. Ratcliff, Mach bands, Holden-Day, San Francisco, 1965, pp. 258–298.

Mitch, D. E., & O'Hagan, S. (1972). Accuracy of stereoscopic localization of small line segments that differ in size or orientation for the two eyes. *Vision Research*, *12*, 437–454.

Ogle, K. (1952). On the limits of stereoscopic vision. *Journal of Experimental Psychology*, *44*, 253–259.

Richards, W. (1973). Reversal in stereo discrimination by contrast reversal. *American Journal of Optometry and Archives of American Academy of Optometry*, *50*(11), 853–862.

Richards, W., & Kaye, M. G. (1974). Local verses global stereopsis: two mechanisms? *Vision Research*, *14*, 1345–1347.

Sato, T., & Nishida, S. (1993). Second-order depth perception with texture-defined random-dot stereograms. *Investigative Ophthalmology and Visual Science*, *34*, 1438.

Schor, C. M., Wood, I., & Ogawa, J. (1984). Spatial tuning of static and dynamic local stereopsis. *Vision Research*, *24*, 573–578.

Schor, C. M., Edwards, M., & Pope, D. R. (1998). Spatial-frequency tuning of the transient-stereopsis system. *Vision Research*, *38*, 3057–3068.

Stuart, G. W., Edwards, M., & Cook, M. L. (1992). Colour inputs to random-dot stereopsis. *Perception*, *21*, 717–729.

Treisman, A. (1962). Binocular rivalry and stereoscopic depth perception. *Quarterly Journal of Psychology*, *14*, 23–37.

Westheimer, G, & Tanzman, I. J. (1956). Qualitative depth localization with diplopic images. *Journal of the Optical Society of America*, *46*(2), 116–117.

Wilcox, L. M., & Hess, R. F. (1996). Is the site of non-linear filtering in stereopsis before or after binocular combination. *Vision Research*, *36*, 391–399.

Wilcox, L. M., & Hess, R. F. (1997). Scale selection for second-order (non-linear) stereopsis. *Vision Research*, *38*, 2981–2992.

Ziegler, L. R., & Hess, R. F. (1999). Stereoscopic depth but not shape perception from second-order stimuli. *Vision Research*, *39*, 1491–1508.