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Spatial-frequency and contrast tuning of the transient-stereopsis system

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Abstract

The tuning of the transient-stereopsis system to luminance contrast and spatial-frequency (SF) was investigated with narrow-band gabor targets with a constant sigma of 1°. They were presented for brief (140 ms) durations and subtended a large (6°) disparity. When dichoptic gabor stimuli were matched in SF (0–5 cpd), transient stereo performance was either uniform across SF or greater at frequencies below 1 cpd. When dichoptic stimuli had unmatched SF (0.5 + 0–5 cpd) and matched contrast (100%), stereo performance was impaired below that of the matched SF condition. Stereo performance with matched SF at 0.5 cpd was impaired when contrast of one eye's image was reduced, demonstrating a contrast-paradox effect (i.e. contrast tuning) for transient stereopsis.

Performance with three dichoptic unmatched SF conditions (0.5 and 1.0 cpd; 0.5 and 5.0 cpd; 1.5 and 3.5 cpd) was improved when the contrasts of the low SF gabor was reduced while holding the contrast of the high SF gabor constant at 100%. However stereo performance was not improved by reducing the contrast of a high SF gabor (3.5 cpd) while holding the contrast of the lower SF gabor (1.5 cpd) constant at 100%. We interpret these findings as indicating that transient-stereopsis performance is mediated by a single spatial-channel that has low-pass spatial-frequency sensitivity and which compares the ocular based signals prior to binocular combination so that signals that are not balanced in terms of their strength lead to a weaker binocular signal, as per the model proposed by Kontsevich and Tyler (Vis Res 1994;3417:2317–2329) for sustained stereopsis. © 1998 Elsevier Science Ltd. All rights reserved.

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Stereoscopic-depth perception appears to be mediated by at least two mechanisms. One system, the sustained or quantitative system, extracts depth from images that are presented for long durations (sensitivity for this system improves as stimulus duration is increased up to about 1 s [1]) and for disparities that are either less than 1° or within Panum's fusional area, which ever is less [2]. The other system, the transient or qualitative system, processes short-duration stimuli at large disparities that are beyond Panum's fusional area [3,4]. A number of studies have presented evidence that suggests that the sustained system exhibits relatively tight spatial-frequency tuning [5,6] however there are alternative explanations [7].

The question of interest in the present paper is to what extent is the transient-stereopsis system tuned to spatial-frequency? Mitchell [8] found that while observers could not fuse two orthogonal line segments that were 0.5° long and 2 min wide, they could extract depth at performance levels that were above chance. Disparities over the range of 0.5 to 4° were tested and the stimuli were displayed for 100 ms. This finding could be interpreted as suggesting that, compared to the sustained-stereopsis system, the transient system may exhibit coarser spatial-frequency tuning [9]. That is the transient-stereopsis system may have been responding to the common low-spatial-frequency information present in the stimuli used by Mitchell. The possibility that the sustained- and transient-stereopsis systems may exhibit differences in their spatial-frequency tuning characteristics is also suggested by the results of studies that have investigated another form of binocular processing; sustained and transient disparity-vergence eye

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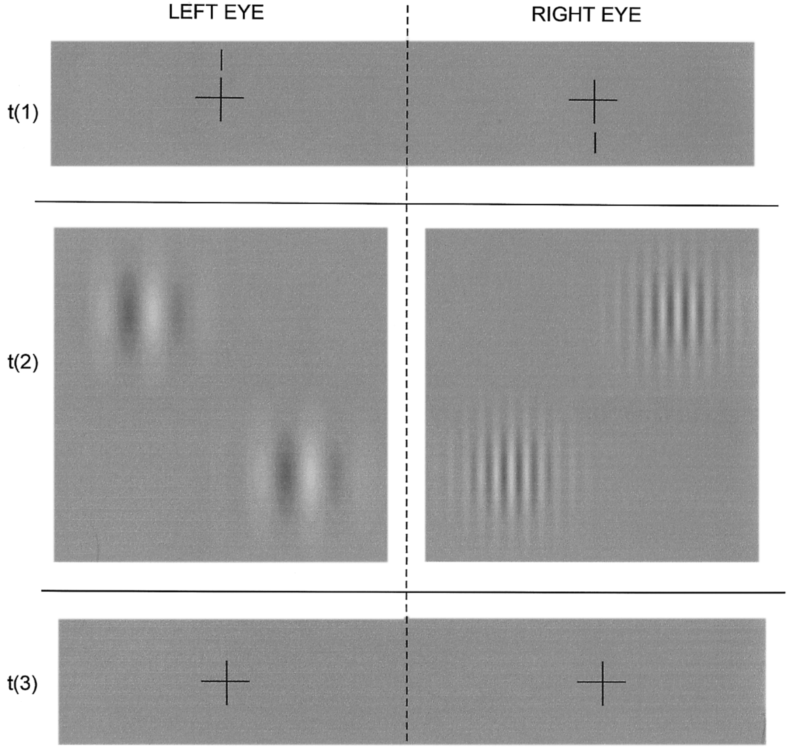

Fig. 1. Schematic showing how the stimuli were presented. Observers first maintained fixation on a pair of crosses and nonius lines (t_1) then, after they had initiated the trial, the test stimulus consisting of two pairs of vertically displaced gabors were presented (t_2). One of these gabor pairs was at an uncrossed and the other at a crossed disparity, relative to the depth that was defined by the fixation cross. After 140 ms, these gabors were replaced by the original fixation crosses, without the nonius lines (t_3).

movements. While the sustained disparity-vergence system appears to be relatively tightly tuned to spatial-frequency [10], the transient system exhibits broadly tuned, low-pass selectivity [11].

1. Experiment 1: spatial-frequency tuning

The aim of the present experiment was to determine whether the transient-stereopsis system exhibits spatial-frequency selectivity. The basic technique that was employed in this analysis was to establish whether performance was better when each stereoscopic half-image had the same spatial-frequency as compared to when the spatial-frequencies differed.

1.1. Method

1.1.1. Observers

Four male observers were used. All had either normal or corrected to normal visual acuity, normal stereopsis and no history of any binocular visual disorders.

1.1.2. Stimuli and Procedure

The stimuli used were gabors with carriers presented in sine phase within a circular Gaussian envelope with a 1° sigma [11] and were presented as shown in Fig. 1. The observer first maintained fixation on a pair of crosses and vertical nonius lines. Once the observer had established fixation with the nonius lines aligned he initiated the presentation of the test stimulus. The test stimuli replaced the fixation cross and nonius lines and consisted of two pairs of dichoptic gabors; with the centers of one pair presented 2.8° above and the other 2.8° below the former center location of the fixation point. One of these pairs was presented at a crossed and the other at an uncrossed disparity relative to the depth that had been defined by the fixation point. The mean disparity of both pairs was 6°, however the amplitude of the actual disparity used was jittered from trial to trial in an anti correlated manner, i.e. if the uncrossed gabor-pair's disparity was increased, the crossed pair's was decreased by the same amount. This was done to ensure that differences in perceived horizontal separation of the diplopic gabors could not be used as a cue to their depth. The magnitude of the jitter added to any given trial was randomly chosen from a set of three values. For DP and CS these values were 0.3, 0.15 and 0° and ME and EG used half of these values since they were less sensitive to this cue. Both crossed and uncrossed disparities were presented to insure that observers with a transient-depth bias [12], would be sensitive to at least one of the two dichoptic pairs of stimuli. The magnitude of the disparity was similar to the disparities we have previously used to investigate the spatial-frequency tuning of the transient-vergence system [11] to allow us to compare the two systems. The observer's task was to indicate which gabor pair (upper or lower) was at the crossed disparity.

Two conditions were used. In the first (matched-frequency) condition, all four gabors in any given trial had the same spatial-frequency; 0 (gaussian) 0.5, 1, 2, 3, 4 or 5 cpd. In the second (unmatched-frequency) condition, gabors that had different spatial-frequency carriers were dichoptically paired. A 0.5 cpd gabor was paired with each of the following frequencies, 0, 1, 2, 3, 4 or 5 cpd (Fig. 1). In any given trial, the pairing used was the same in both the upper and lower gabor pairs. The 0.5 cpd gabor was presented to either the right or left eye in both the upper and lower stimulus pair, and the variable spatial-frequency gabor was presented to the other eye. For ease of comparison, we used the same size gaussian envelope (standard deviation of 1°) for all of the carrier frequencies used and the contrast of all gabors was 100%. We are currently conducting experiments to determine whether there is any link between carrier frequency, envelope size and the disparity offset of the gabors. It has previously been shown that placing stereoscopic images close to one another degrades performance; the so-called crowding effect [13]. To ensure this did not occur with the present stimuli, a vertical gap of 1.35° was maintained between the upper and lower pairs of gabors. This was achieved by clipping the top vertical extent of the lower gabors and the bottom vertical extent of the upper ones. The temporal duration of the stimuli was 140 ms and feedback as to the correctness of their response was given to the observers. The viewing distance was 1.0 m. Stimuli were presented in ten blocks of 20 trials each in which the spatial-frequencies used in each trial were kept constant. Data was collected over several days. In the unmatched-frequency condition, the location of the crossed disparity and the eye to which the low-frequency gabors were presented were randomised from trial to trial.

1.1.3. Apparatus

Stimuli were generated using a Cambridge Research Systems VSG 2/3 graphics card in a host Pentium computer and were displayed on a 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 stabilize the observer's head.

1.1.4. Results and discussion

The results for the four observers are shown in Fig. 2. Performance, measured as percentage of the responses that were correct, is plotted against the spatial-frequency of the gabors for both the matched and unmatched spatial-frequency conditions. Error bars represent plus and minus one standard error of the means of the ten data blocks. The standard errors were recomputed in terms of the binomial distribution and the results were the same as the current measure indicating that subjects performance levels were consistent from day to day. In the unmatched condition, the abscissa value refers to spatial-frequency of the gabor that was paired with the 0.5 cpd gabor. For three of the observers (CS, DP and EG) performance in the matched-frequency condition was best at low spatial-frequencies and declined as the spatial-frequency was increased. This decline in performance was most pronounced for EG. This optimal performance was not centered on 3 cpd which would be expected from the contrast-sensitivity function for short-duration stimuli [14]. Rather, the optimal spatial-frequency tuning for transient stereopsis (0–0.5 cpd) was similar to that which has been observed for the transient-vergence system [11]. The fourth observer (ME) showed substantially constant performance over the frequency range tested. This pattern of results was also reported recently by Landers and Cormack [15]. For two of the observers, CS and DP, performance at low frequencies was close to 100% and it dropped to 80% and 70% at higher spatial-frequencies whereas ME performed at a constant 80% across all spatial-frequencies tested.

For all observers, performance for the unmatched-frequency conditions was substantially worse than that obtained for the matched-frequency conditions. Note that this decrement in performance occurred even when there was only a relatively small spatial-frequency difference in the gabors e.g. when 0.5 cpd was paired with 1 cpd. In this sense, the observed results are markedly different from those obtained for the transient-vergence system, which showed preferential performance for the unmatched spatial-frequencies (low paired with a high) as compared to matched (two high) spatial-frequencies [11]. Note also that while three of the observers exhibited worse performance for the unmatched-frequency condition for all of the differential spatial-frequency combinations, DP's performance at 0 cpd is the same as that for the matched condition. This finding may indicate that pairing a 0.5 cpd gabor with a 0 cpd (gaussian) one did not impair DP's performance, relative to that for paired gaussians. However it may also mean that our measure was not sufficiently sensitive. That is, given DP's strong performance for this task, especially at low frequencies, small reductions in signal strength due to the mixed-frequency pairing may not have resulted in a decrease in performance, i.e. we may have

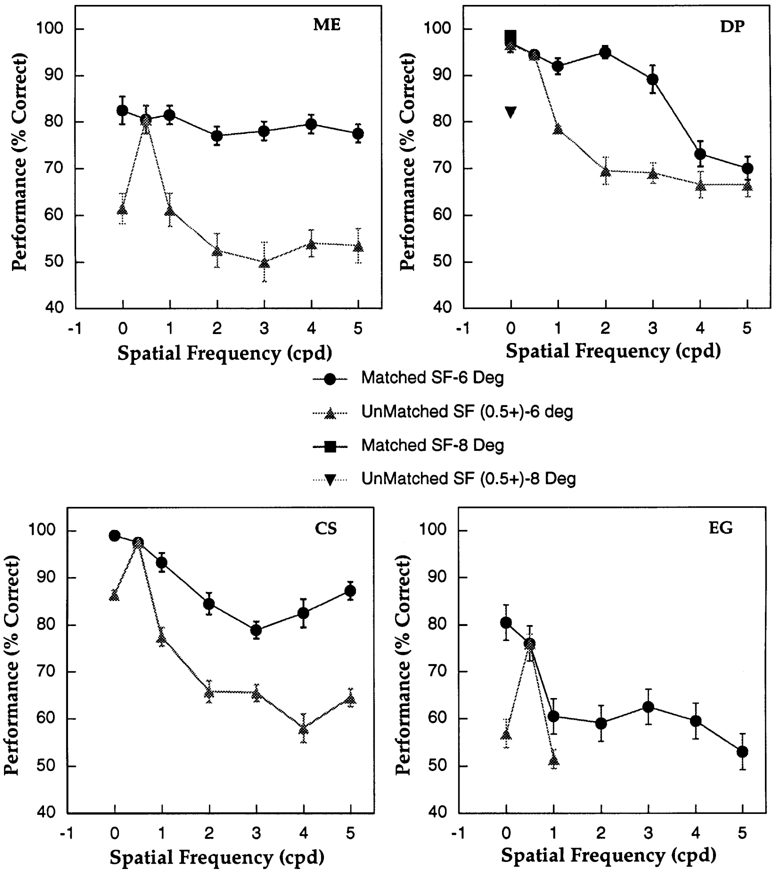

Fig. 2. Results for Experiment 1. Performance (percentage of responses that were correct) is plotted against the spatial-frequency of the gabors. Error bars indicate plus and minus one standard error of the mean. Two conditions were used: a matched spatial-frequency condition (Matched SF) in which the spatial-frequency of the gabors was the same and an unmatched spatial-frequency condition (Unmatched SF) in which a 0.5 cpd gabor was paired with a gabor of a different frequency. All observers were tested at 6° disparity and DP was further tested at 8° disparity. For the unmatched SF condition, the frequency of the second gabor is given by the abscissa. Performance on the Matched SF condition is substantially better than that for the unmatched SF condition for all observers.

encountered a floor effect. To test for this possibility we increased the difficulty of the task, by increasing the disparity of the stimuli to 8°, and retested DP under these two conditions. As can be seen from Fig. 2, DP's performance for the unmatched condition was worse than that for the matched condition.

The simplest way to interpret the roll off in performance in the unmatched-frequency condition as the spatial-frequency of the gabors was varied from the matched 0.5 cpd condition is to propose that transient stereopsis is mediated by a system that is composed of a number of channels that are tightly tuned to spatial-frequency. However, based upon the work of Kontsevich and Tyler [7], there is another possible interpretation. Similar to the present findings, Schor et al., [6] found that performance for sustained stereopsis was impaired as the difference in spatial-frequency between the two dichoptic half-images was increased, as compared to the condition in which the spatial-frequencies were matched. Difference of gaussian stimuli were used in their study. This impairment in performance was particularly pronounced for spatial-frequencies below 2.5 cpd. Schor et al. interpreted this finding as indicating the existence of multiple narrow-band spatial-frequency tuned channels below 2.5 cpd, and more broadly-tuned channels above 2.5 cpd. Kontsevich and Tyler [7], proposed an alternative model which not only accounts for the Schor et al. finding but also, amongst other findings, the so-called contrast-paradox effect. This effect is the observation that sustained stereopsis is better when the dichoptic half-images have equal low contrast, as compared to when the contrast of one of the half-images is raised [16–18]. Unlike the Schor et al. model, Kontsevich and Tyler proposed that spatial-frequencies below 2.5 cpd are processed by a single spatial-frequency-tuned channel, and that prior to the binocular combination of the signals from both eyes, the two ocular-based signals inhibit each other in some manner. The consequence of this inhibitory link is that the resultant signal at the binocular combination stage will be lower when the signals from each eye are at different strengths, as compared to when they are matched. Differences in signal intensity between the two eyes can occur when to the two eyes are presented with different contrasts (resulting in the contrast-paradox effect which could be referred to as contrast tuning) or different spatial-frequencies to which the system has differential sensitivity (resulting in a pattern of performance obtained in the present study and by Schor et al. [6]).

In the Kontsevich and Tyler model for sustained stereopsis, the lowest spatial-frequency-tuned channel has a center frequency of 2.5 cpd. In order for a single broad-band channel to account for the present finding that best performance in the matched-frequency condition occurs at low frequencies (in the range of 0–0.5 cpd) the putative single channel mediating transient-stereoscopic performance would need to exhibit low-pass spatial-tuning. The first step in determining whether such a model could account for the present results is to determine whether the contrast-paradox effect occurs for transient stereopsis.

2. Experiment 2: the effect of differential contrast on transient stereo-performance

The aim of the present experiment is to determine whether, like the situation for sustained stereopsis [16–18], the contrast-paradox effect occurs for transient stereopsis. That the transient-stereopsis system may not exhibit this feature is suggested by the observation that transient vergence does not exhibit contrast tuning, i.e. the contrast-paradox effect. Observers are more likely to initiate a vergence response to dichoptic half-images of dissimilar, high- and low-contrast stimuli, than they are to two low-contrast stimuli [11].

2.1. Method

2.1.1. Stimuli and procedure

The spatial-arrangements of the stimuli were the same as that used in Experiment 1. Two stimulus conditions were employed. In the first condition (matched-contrast), all four gabors in any given trial had the same luminance contrast while in the second condition (unmatched-contrast), the left and right gabors in both the upper and lower dichoptic pairs had different contrasts. The contrast in the matched condition varied from 100% to 20%. In the unmatched condition, the contrast of one eye's stimulus, the fixed gabor, was kept at 100% while the contrast of the other eye's stimulus, the variable gabor, was lower (Fig. 3). Gabors with a spatial-frequency of 0.5 cpd were used and five contrasts (100, 80, 60, 40 and 20%) were employed.

2.1.2. Results and discussion

The results for the four observers are shown in Fig. 4. For three of the observers, performance for the matched-contrast condition was substantially constant over the contrast range used, while the fourth observer (EG) improved at lower contrasts. For the unmatched-contrast condition, performance became progressively worse as the contrast of the variable gabor was decreased such that at low contrasts, the performance for the unmatched condition (in which the contrast of one gabor was 100% and the other was reduced, e.g. 60%) was lower than that for the matched condition (in which the contrast of both dichoptic gabors was reduced, e.g. 60%). The magnitude of this reduction in performance differed for the four observers with DP showing the smallest reduction in performance. To determine whether this was due to a floor effect as observed in Experiment 1, we retested DP at 8° disparity. As can be seen from Fig. 4, doing this increased the rate at which his performance for the unmatched condition rolled off, as compared to the matched condition. These results show that, unlike the transient-vergence system [11] the transient-stereopsis system displays the contrast-paradox effect.

3. Experiment 3: unmatched spatial-frequencies with differential contrasts

The results of Experiment 2 indicate that having dichoptic half-images of dissimilar contrasts impairs transient-stereopsis performance. Such a finding is consistent with the predictions of a Kontsevich and Tyler type model. With such a model, impaired performance is due to different activity levels in the two ocular-based channels. Differences in activity levels can result from presenting either different spatial-frequencies or contrasts to the two eyes when channels are tuned to both

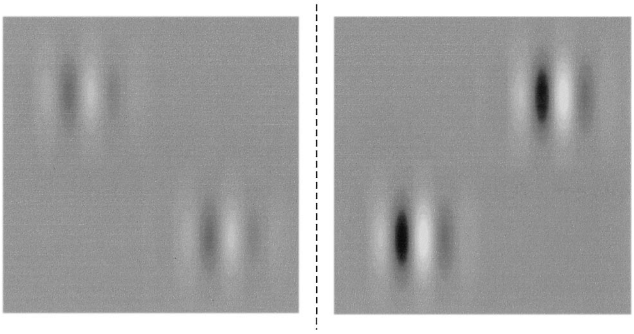

Fig. 3. Stimuli used in Experiment 2. All gabors had the same spatial-frequency (0.5 cpd) but their contrasts were varied. Since the aim of the experiment was to determine whether the transient-stereopsis system displays the contrast-paradox effect, the contrast of one of the gabors in a dichoptic pair was maintained at 100%, while that of the other one was varied between 20 and 100%. All observers were tested at 6° disparity and DP was further tested at 8°.

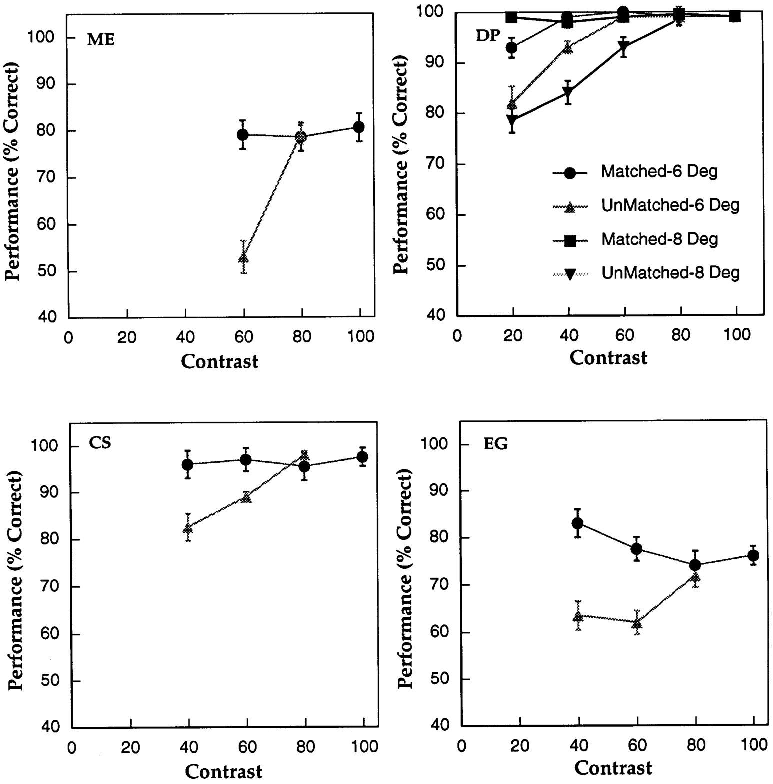

Fig. 4. Results for Experiment 2. Stimuli used were 0.5 cpd gabors that had either matched (Matched condition) or dissimilar (Unmatched condition) contrasts. In the Unmatched condition, the contrast of one of the gabors was maintained at 100% and that of the other one is given by the abscissa value. As the contrast of one (Unmatched) or both (Matched) gabor/s is decreased, all observers exhibit better performance for the matched condition than for the unmatched one. That is, the contrast-paradox effect holds for transient stereopsis.

of these parameters. As Kontsevich and Tyler [7] state, a prediction from such a model is that by varying both the spatial-frequency and contrast of the stimuli presented to the two eyes, it should be possible to balance the activity in each ocular channel and hence improve performance. That is, optimal performance for the unmatched spatial-frequencies condition employed in Experiment 1 should be obtained when the contrast of the spatial-frequency to which the system shows greater sensitivity is lower than the contrast of the other spatial-frequency. Based upon the results of Experiment 1, this means that when a 0.5 and 1 cpd gabor are paired, performance should improve when the contrast of the 0.5 cpd gabor is below that of the 1 cpd gabor, and optimal performance should be obtained at relative contrast levels for the two gabors that result in the same level of activity in the two ocular-based channels that process the two different spatial-frequencies. The aim of this experiment was to see if this prediction could be verified.

3.1. Method

3.1.1. Stimuli and procedure

The spatial-arrangement of the stimuli was the same as that used in previous experiments. Gabors of 0.5 and 1 cpd were paired to form horizontal disparities and the contrast of the 1 cpd gabor was held constant at 100% while that of the 0.5 cpd gabor was decreased in 20% steps.

3.1.2. Results and discussion

The results for the four observers are shown in Fig. 5. Performance (percent correct) is plotted against the contrast of the 0.5 cpd gabor. The contrast of the 1 cpd gabor was held constant at 100% thus the 100% contrast point on the abscissa represents the condition in which the two gabors had the same contrast. The horizontal line indicates stereo performance with matched 1 cpd gabors at 100% contrast. The basic pattern of results is the same for all observer. Optimal performance with unmatched spatial-frequencies was obtained when the contrast of the 0.5 cpd gabor was substantially below that of the 1 cpd gabor, though for observer CS this effect is quite mild. Such a finding supports a Kontsevich and Tyler type model to account for the present results; a broad-band channel that has some form of inhibitory link between the two ocular inputs.

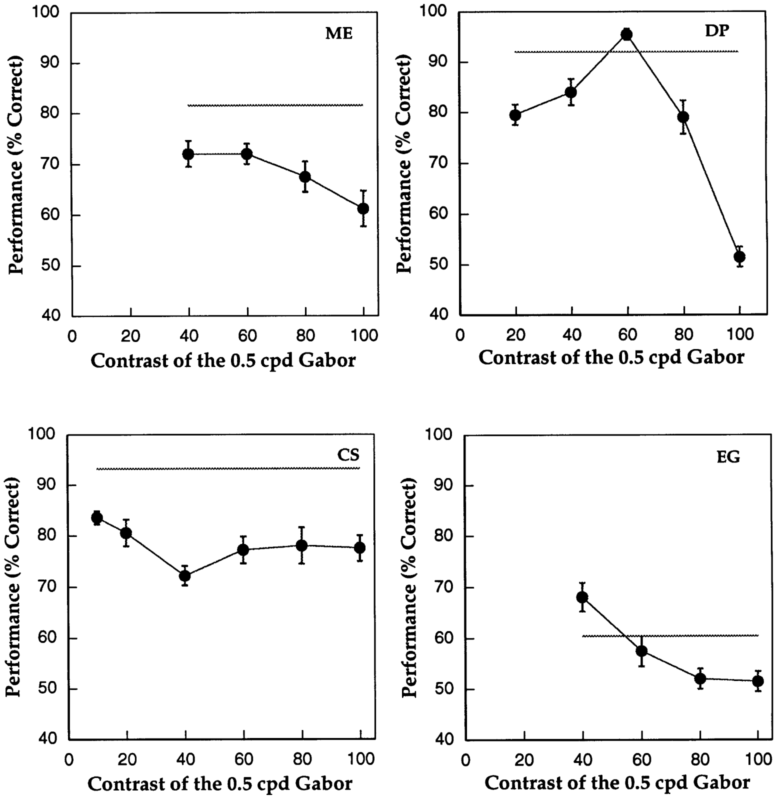

Fig. 5. Results for Experiment 3. A single condition was used in which a 0.5 cpd gabor was paired with a 1 cpd gabor. The contrast of the 1 cpd gabor was maintained at 100% while that of the 0.5 gabor was varied—values given by the abscissa. All observers showed best performance when the contrast of the 0.5 cpd gabor was lower than that of the 1 cpd gabor; though this effect is slight for CS. The horizontal line in each graph indicates stereo performance with matched 1 cpd gabors at 100% contrast.

4. Experiment 4: a broad-band channel?

The finding from the previous experiment that optimal performance for unmatched spatial-frequencies was achieved when the contrast of the low-frequency (0.5 cpd) gabor was lower than that of the high-frequency (1 cpd) gabor supports a model of a transient-stereoscopic mechanism that employs a Kontsevich and Tyler type single broad band spatial-frequency-tuned channel; with the peak sensitivity of that channel being in the order of 0 to 0.5 cpd. Kontsevich and Tyler proposed a band-pass channel to explain stereo performance with small sustained disparities and we propose a low-pass channel to account for stereo performance with large transient disparities. However the present result is also compatible with a model that employs multiple-independent narrow-band spatial-frequency-tuned channels, with each channel possessing the inhibitory links between ocular based signals used in the Kontsevich and Tyler model. That is, each channel would display contrast-paradox-type behavior (Fig. 6). Further support for a low-pass broad-band channel would be obtained if a similar pattern of results to that obtained in Experiment 3 was obtained with disparate, 0.5 and 5 cpd, spatial-frequencies.

4.1. Method

4.1.1. Stimuli and procedure

The experimental procedure was the same as that used in Experiment 3, except that spatial-frequencies of 0.5 and 5 were used. The contrast of the 5 cpd gabor was held constant at 100% and that of the 0.5 cpd gabor was reduced to see if a contrast could be found at which performance improved. Only three of the previous observers were used since EG's sensitivity to matched high-spatial-frequency stimuli was too low (Fig. 2).

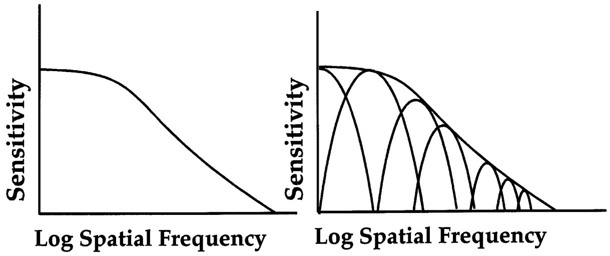

Fig. 6. The two main ways in which the transient-stereopsis system could be tuned to spatial-frequency. (a) A single low-pass tuned spatial-frequency channels. (b) Multiple narrow-band spatial-frequency tuned channels.

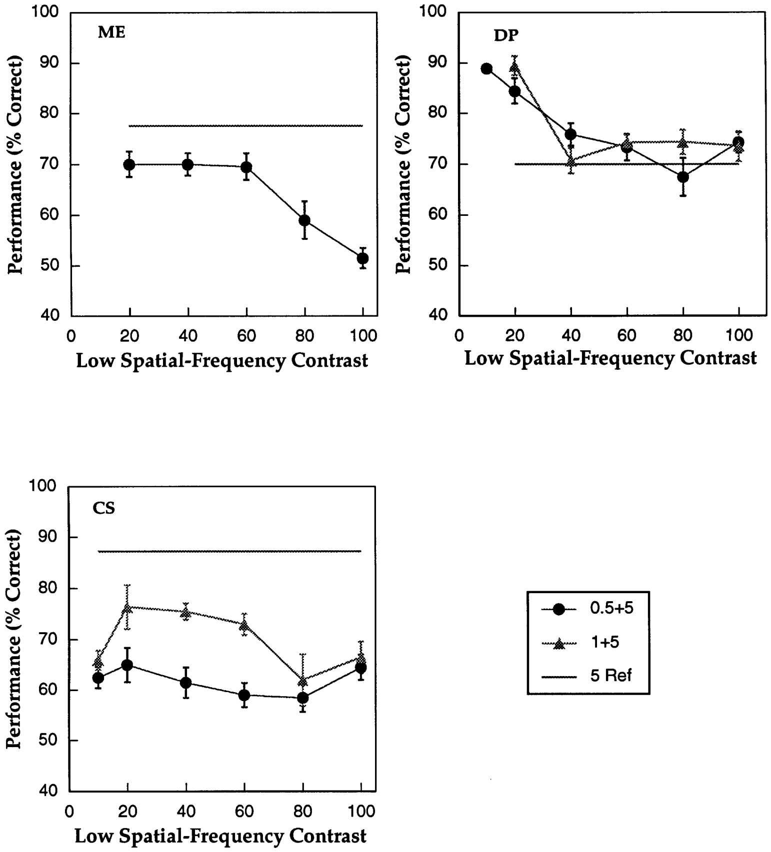

Fig. 7. Results for Experiment 4. Two conditions were used. In the first condition (0.5 + 5) 0.5 and 5 cpd gabors where paired solid circle symbols) and in the second (1 + 5) 1 and 5 cpd gabors where paired (triangle symbols). In both conditions, the contrast of the lowest spatial-frequency gabor was varied (value given on the abscissa) while that of the 5 cpd gabor was kept constant at 100%. The solid line indicates the observer's performance with matched 5 cpd gabors. The performance of ME and DP on the 0.5 + 5 condition improved as the contrast of the 1 cpd gabor was lowered (over a certain contrast range) while it did not for CS. However (CS and DP) did show improvement in the 1 + 5 condition. These results support the notion that performance is mediated by a low-pass broad-band channel.

4.1.2. Results and discussion

The results for the Experiment 4 are shown in Fig. 7. The horizontal lines represent stereo performance with matched 5 cpd gabors at 100% contrast. The pattern of results for unmatched spatial-frequencies differ for the three observers. Observers ME and DP showed a marked improvement as the contrast of the 0.5 cpd gabor was decreased while CS showed no systematic improvement in performance (solid circle symbols). For ME, performance improved as the contrast of the 0.5 cpd gabor was reduced to 60% contrast, after which performance was fairly constant, while DP's performance continued to improve as contrast was reduced to 10%. The failure of CS to show any improvement in the present task could be accounted for by referring to his results from Experiment 2 (Fig. 4). The magnitude of the contrast-paradox effect, exhibited by CS, measured with matched spatial-frequency, is relatively mild (15% reduction with pairing of 100 and 40% contrast), especially when compared to that exhibited by ME (28% deficit with pairing of 100 and 60% contrast) (Fig. 4). Similarly, for CS at least, in the unmatched spatial-frequency condition (0.5 and 1 cpd gabors—Experiment 3) the improvement in performance as the contrast of the 0.5 cpd gabor was decreased was slight and only occurred at the lowest contrast level used; 10% (Fig. 5). These findings could suggest that the variation in the activity level of the monocular inputs sensitive to the 0.5 cpd gabor, produced by varying the luminance-contrast level, is slight for CS or that the activity level for the 0.5 cpd gabor is much greater that for the 5 cpd gabor such that it is impossible to equate their signal strength and keep the 0.5 cpd gabor visible. Thus it may be difficult to match the activity in the two monocular channels to the two different spatial-frequencies by lowering the contrast of the 0.5 cpd gabor. In an attempt to test this possibility, we retested CS using 1 and 5 cpd gabors. DP was also tested with this condition. For this frequency pairing both observers showed improvement in performance as the contrast of the lowest spatial-frequency (1 cpd) was reduced (Fig. 7, triangle symbols). Thus all observers show evidence for a Kontsevich and Tyler type broad-band channel.

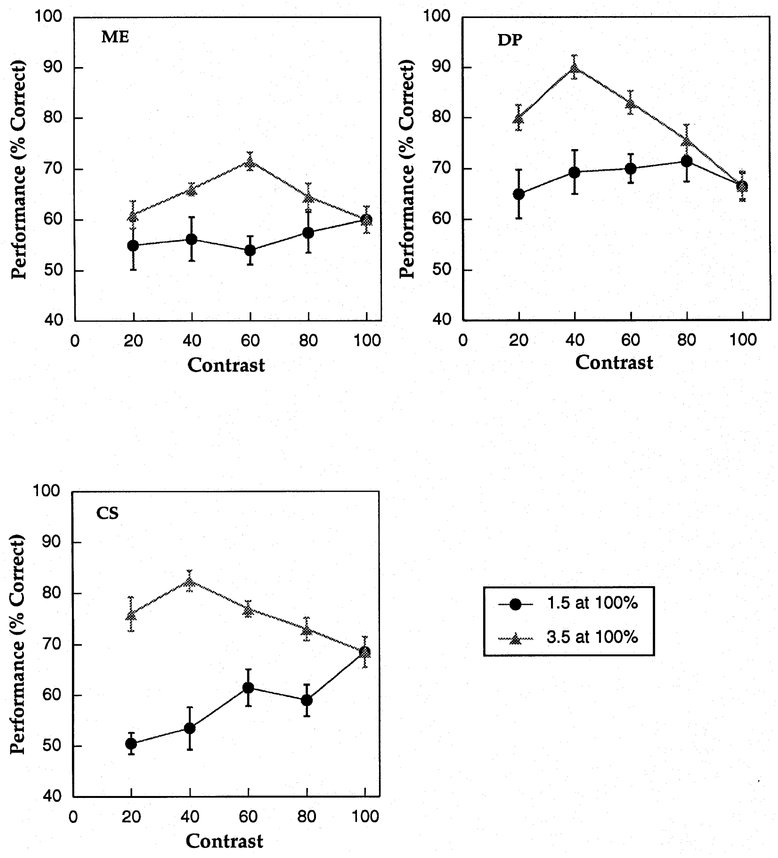

Fig. 8. Results for Experiment 5. Two conditions were used, both of which paired 1.5 and 3.5 cpd gabors. In one condition (1.5 at 100%) the contrast of the 1.5 cpd gabor was held constant at 100% and that of the 3.5 cpd was reduced (solid circle symbols) while in the other (3.5 at 100%), the opposite manipulation occurred (triangle symbols). For all observers, performance initially improved as the contrast of the 1.5 cpd gabor was reduced while reducing the contrast of the 3.5 cpd gabor did not improve performance. These results do not support the notion that transient-stereoscopic performance is mediated by multiple spatial-frequency-tuned channels, at least over this frequency range.

5. Experiment 5: multiple narrow-band channels?

The results from the above experiment support the notion that transient-stereopsis performance is mediated by a single broad-band channel. However, the mere existence of a broad-band channel does not rule out the possible existence of additional narrow band channels. To test for this possibility we ran two conditions in which intermediate spatial-frequencies (1.5 and 3.5 cpd) were employed and the contrasts were varied in both directions. That is, in one condition the contrast of the 1.5 cpd gabor was held constant at 100% and the contrast of the 3.5 cpd gabor was decreased in 20% steps while in the other condition the contrast of the 3.5 cpd gabor was held constant at 100% and that of the 1.5 cpd gabor was decreased. If a single spatial-frequency-tuned channel solely mediates transient-stereopsis performance (at least over the disparity and frequency ranges used in the present study) then it should be possible to balance the response of that channel to two different spatial-frequencies by varying their relative contrasts in one direction only—e.g. by decreasing the contrast of the 1.5 cpd gabor relative to the 3.5 cpd gabor. Decreasing the contrast of the 3.5 cpd gabor relative to the 1.5 cpd gabor would increase the difference in activity to the two stimuli and hence increase the contrast-paradox effect. However, if multiple narrow-band frequency-tuned channels are employed then it should be possible to vary the contrast of either gabor relative to the other and be able to balance the response to the stimuli in one of the several channels tuned to different frequencies; with the responses being balanced in different channels depending upon which spatial-frequency is decreased relative to the other.

5.1. Method

5.1.1. Stimuli and procedure

The experimental procedure was the same as that used in Experiment 3, except that spatial-frequencies of 1.5 and 3.5 were used and the contrasts were varied in both directions. That is in one condition, the contrast of the 1.5 cpd gabor was held constant and that of the 3.5 cpd gabor was reduced and in the other condition the reverse manipulation occurred.

5.1.2. Results and discussion

The results for the three observers are shown in Fig. 8. The pattern of results is the same for all observers. Performance was improved only when the contrast of the 1.5 cpd gabor was lowered relative to the 3.5 cpd gabor (triangle symbols), not when the reverse manipulation was performed (solid circle symbols). Thus these results do not support the concept of multiple narrow-band channels; at least over the frequency range tested, and at least at the level of the cross-channel inhibitory link. That is, it is possible that multiple narrower-band channels exist, but that the output of these channels is pooled to form a single (monocular) channel prior to the cross inhibition stage.

6. General discussion

The present results indicate that: the ability of observers to extract transient depth from gabors is impaired when the contrasts of the dichoptic gabors are matched but the spatial-frequencies are unmatched—as compared to the condition in which both the spatial-frequencies and contrasts are matched (Experiment 1); the contrast-paradox effect holds for transient stereopsis-that is with matched spatial-frequencies, performance for unmatched luminance contrasts is worse than that for matched contrasts, i.e. the system shows contrast tuning (Experiment 2); best performance with unmatched spatial-frequencies is obtained when the contrasts of the different spatial-frequencies are also different (Experiment 3); this improvement in performance is achieved by varying the relative contrasts of the different spatial-frequencies, even for markedly different frequencies (e.g. 0.5 and 5 cpd gabors—Experiment 4) and that this improved performance with unequal spatial-frequencies can exceed performance with matched high spatial-frequencies of equal high (100%) contrast (Figs. 5 and 7, observers DP and EG). Finally, for similar intermediate frequencies (1.5 and 3.5 cpd), improved performance is achieved only when the relative contrasts are varied in one direction; the contrast of the 1.5 cpd gabor is lowered relative to that of the 3.5 cpd gabor, but not in the other (Experiment 5).

The basic finding that performance is better with matched spatial-frequencies than with unmatched frequencies with equal contrast indicates that transient stereopsis is mediated by a system that incorporates some form of spatial-frequency tuning. While the simplest explanation to account for this observed tuning would be to propose the existence of a number of narrow band channels [6], the additional findings that performance improved when the contrast of a low spatial-frequency was reduced relative to that of a higher spatial-frequency in a dichoptic pair supports a type of model similar to that proposed by Kontsevich and Tyler [7] to account for sustained stereopsis. That is, the two ocular-based signals of a single broad-band spatial-frequency tuned channel interact prior to binocular combination, causing a reduction of binocular activity when the two signals have different strengths. The activity in each ocular channel can be altered by varying either the contrast or the spatial-frequency presented to that eye, hence making it possible to balance the activity in each ocular channel when different spatial-frequencies are presented to the two eyes by varying the relative contrasts of the two frequencies.

Further support for a single broad-band mechanism, as opposed to a number of narrow-band channels with each employing this type of ocular based interaction, comes from two additional findings. The first is that the observed improvement in performance achieved by varying the relative contrasts of the different spatial-frequencies occurs even for markedly different frequencies; 0.5 and 5 cpd for ME and DP and 1 and 5 cpd for observer CS. The second finding is that with the 1.5 and 3.5 cpd gabors, performance was only improved by decreasing the contrast of the 1.5 cpd gabor relative to the 3.5 cpd gabor. Varying the contrasts in the opposite direction did not improve performance. If there were functionally-independent multiple narrow-band channels at the level where interocular inhibition occurs, then it would be reasonable to assume that it should be possible to vary the contrast of either gabor relative to the other and be able to balance the response to the stimuli in one of the channels. Balanced responses in different channels would depend upon which spatial-frequency was decreased relative to the other (Fig. 6). Thus if multiple narrow-band channels exist, we should have found that performance improved in both conditions; i.e. when the relative contrast of the 1.5 cpd gabor was increased and when that of the 3.5 cpd gabor was increased. That this was not the case (performance improved only when the relative contrast of the 1.5 cpd gabor was decreased) supports the single-channel model; although, this channel may pool the outputs of a number of narrower-band channels (first-order mechanism), or it could emerge from a non-linear extraction of low frequencies from the gabor envelope (second-order mechanism).

Note that this logic can also account for the observed lack of a contrast-paradox in the sustained-stereopsis system at high spatial-frequencies [16–19]. Given that for sustained-stereoscopic processing, multiple channels appear to exist which have overlapping spatial-frequency-tuning profiles in the high spatial-frequency range (> 2 cpd) but which are optimally tuned to different spatial-frequencies [5] then such balancing of the ocular responses to different spatial-frequencies and or contrasts would be possible. The lack of a contrast-paradox effect for matched high spatial-frequencies could be accounted for by proposing that the binocular units receive inputs from channels with different center frequencies. Monocular signal strengths would be matched when the channel processing the high-contrast stimulus was optimally tuned to a slightly different spatial-frequency than the stimulus and the channel processing low-contrast stimulus was optimally tuned to the same spatial-frequency as the stimulus.

Similarly the finding by Schor et al., [6] that mixing spatial-frequencies at high (> 2 cpd) spatial-frequencies did not overly impair performance (a finding which they interpreted as indicating broad spatial-frequency tuning) can also be accounted for by using a similar logic. Dichoptic stimuli composed of gabors of different spatial-frequencies but the same contrast could be processed by channels that had different spatial-frequency tuning, if the two monocular channels had equal relative sensitivity to their respective stimuli. Such a situation would result in ocular inputs of the same signal strength and hence no reduction in performance, as was observed by Schor et al., [6].

It is interesting to note the peak spatial-frequency sensitivity of this single channel. Given that when 0.5 and 1 cpd gabors were paired (Experiment 3) the contrast of the 0.5 gabor had to be decreased relative to that of the 1 cpd. It would appear that peak sensitivity is about 0.5 cpd or lower. This value is similar to that obtained for the transient-vergence system [11] and lower than that obtained for the sustained-stereopsis system, which is in the order of 2.5 cpd [7,6]. While the spatial-frequency tuning of the transient stereo and vergence systems appear to be similar, they differ in their response to matched frequencies with mismatched contrasts. The transient-stereopsis system exhibits the contrast-paradox effect while the transient-vergence system does not [11]. Thus while the initial filters that provide input to both systems have a similar frequency tuning, and are possibly the same filters, the manner in which both systems process these inputs differ. Transient stereopsis, like sustained stereopsis [16–18] requires equal strength of the two ocular-based signals while the transient-vergence system does not. The probability that a dichoptic stimulus of unequal contrast will evoke a transient vergence responses increases with combined (left eye plus right eye) image contrast.

In relation to the issue of the spatial-frequency tuning of the transient-stereopsis system, it is worth noting that at the relative contrasts for which optimal performance was obtained, the perceived contrast of the different frequencies were markedly different. For example, when 0.5 and 1 cpd gabors were paired, best performance was obtained when the perceived contrast of the 0.5 cpd gabor was markedly lower than that of the 1 cpd gabor. Georgeson and Sullivan [20], found that in a perceived-contrast-matching experiment, observers veridically matched the contrasts of suprathreshold gratings of different spatial-frequency. Also Schor and Howarth [21], showed that for difference-of-gaussian stimuli, perceived contrast was largely independent of spatial-frequency at high (> 25%) contrasts. At lower contrasts, low frequencies (< 1.2 cpd) required higher contrast. These findings, when combined with the present results, indicate that the 'matching' of stimuli as far as the transient-stereopsis system is concerned is not the same as matching them within the system that mediates perceived contrast. Such a finding is consistent with the observation that the frequency tuning of transient stereopsis peaks at a low frequency. Both monocular detection and sustained-stereopsis peak at a higher frequencies (3 cpd) [14] and (2.5 cpd) [7] respectively, which are more likely to be related with the system that is responsible for mediating perceived contrast.

The final issue of note from the present results concerns the degree of improvement obtained by varying the relative contrasts of the different spatial-frequencies. From Figs. 5 and 7 it can be seen that the degree of improvement in performance as the contrast of the lowest spatial-frequency gabor was increased varied amongst the observers. When the contrast of the 0.5 cpd gabor was reduced relative to that of the 1 cpd gabor (Fig. 5) both DP and EG obtained a performance level for the unmatched-frequency condition that was actually better than their performance for matched 1 cpd gabors. In contrast, while the performance of ME and CS improved as the contrast of the 0.5 cpd was reduced, it never achieved the same level as that for the matched 1 cpd condition. Similarly, improvements were observed for the conditions in which very disparate spatial-frequencies were paired (0.5 and 5 cpd and 1 and 5 cpd, Fig. 7). In these conditions, DP actually starts off at a performance level that is about equal to that for matched 5 cpd gabors and improves from there, while CS and ME never attain the level they achieved with matched 5 cpd gabors.

There are at least two possible reasons for this variation between the observers. The first is that it is possible that we did not perfectly match the contrasts for the different frequencies. Such a possibility is likely since we used relatively coarse contrast step-sizes of 20%. Hence in the unmatched-frequency conditions there still could have been an imbalance in the two ocular-based signals which, within the logic of the model, would have impaired performance. However, while this explanation could account for the failure of both ME and CS to attain higher performance levels for the unmatched-frequency conditions, it doesn't account for DP and EG's elevated performance levels. Thus it is also possible that performance on the two types of conditions, unmatched frequencies and matched frequencies, may be mediated by different processes which have different stereo-sensitivities. We are currently exploring this possibility.

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