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INDUCED STEREOMOVEMENT

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Abstract—Temporal limitations of three-dimensional shape constancy were investigated by measurement of the perception of movement in an oscillating random-dot stereogram. The departure from shape constancy produced by this stimulus induces apparent movement in the stereoscopic figure. This induced stereomovement is best perceived at low oscillation frequencies. Perception of induced stereomovement differs from perception of monocular movement or previously observed types of stereomovement.

INTRODUCTION

Human observers have the ability to perceive rigid objects in the environment as having an approximately constant shape despite rotations in three dimensions of the object relative to the observer. The remarkable amount of visual processing required to perform this task perfectly was discussed by Helmholtz (1894) in one of his last works. The degree to which three-dimensional shape constancy is actually achieved was first measured by Thouless (1931). Using the somewhat artificial object of a circular disk, he found that observers made an approximately equal compromise between the retinal image and the real object in matching the shape of the object. Later experiments reviewed by Bartley (1969) show that degree of shape constancy depends in a complex fashion on the experimental situation and type of stimulus. Leibowitz, Mitchell and Angrist (1954) found that shape constancy tended to increase with increased exposure times, whereas size and brightness constancy did not. Recently, Massaro (1973) has measured reaction time for accurate perception of shapes slanted in depth. He reports that reaction times increase by up to 1 sec as slant is increased, while reaction times for discrimination of the fronto-parallel projections of the same figures remain constant. The results of both studies were interpreted as demonstrating that shape constancy in depth involves a slow perceptual process relative to that for shape discrimination, but it is possible that the processing of depth cues alone was the retarding factor. Another possible artefact is the presence of luminance changes when the stimuli are presented, which might specifically mask the depth cues or disturb the shape constancy process.

The present study is designed to compare sensitivity to depth cues and to shape variations as a function of temporal parameters, using stimuli involving no luminance transients during presentation. This will be achieved by measuring the perception of departure from constant shape when an object is distorted during rotation. A convenient method of producing such a distortion is by the use of Julesz (1964) random-dot stereograms containing a stereoscopic figure invisible in monocular view. It is well-known that on observation of such stereograms in anaglyph (two-colour) form, the figure standing out will seem to follow movements of the head so as to be always "pointing" towards the observer. This distortion of the figure needs to be explained since there is no corresponding movement in the texture of the surfaces of the stereoscopic figure. Julesz (1971) and Lee (1969) have given differing explanations of this phenomenon, which will be called induced stereomovement.[1] Lee (1969) describes an equivalent movement produced by a stereoscopic shadow-caster, which operates on the same principles as the Julesz figure although the shadow-caster contains monocular as well as stereoscopic cues to the figural changes. Relative movement of the observer towards or away from the stereogram produces a decrease or increase in the perceived extension of the figure in proportion to distance moved. The apparent size and shape of fronto-parallel surfaces remain constant, since their retinal subtense decreases in inverse proportion to distance of the observer. Lee suggests that relative movement of the observer in a plane parallel to the stereogram produces a shearing of the fronto-parallel planes (surfaces). This shearing must be solely in the perceptual system since there is no actual shearing of the images of these surfaces on the retina. (In contrast, movement of the observer past a real object does produce shearing of the fronto-parallel surfaces on the retina.) Paradoxically, the absence of shearing in the stereoscopic figure is experienced as movement by all observers I have encountered who perceive the depth of the figure. This paradox is not entirely symmetrical,

[1] The term "induced stereomovement" has been used by R. Weldon, D. Slingerland, and J. Myers [*Human Factors* (1968)**10**, 385] to imply simply an artificially generated stereomovement. I suggest it is more appropriate to reserve it for the constancy-induced movement reported here.

because in spite of a tendency to perceive real objects as rigid and static when the observer moves past them, most observers report that relative shearing of the surfaces can also be perceived. It seems that the perception of movement occurs whether the distal or the proximal object remains constant, suggesting that three-dimensional shape constancy operates but is inefficient. Lee's analysis of induced stereomovement is therefore incomplete, in that he does not take account of the perceptual processes involved.

Julesz (1971) makes the point that stereopsis persists when the observer moves past a stereogram, in spite of the presence of perception of movement in the figure correlated with head movements, and that stereopsis is therefore a stronger depth cue than apparent motion parallax. He calls the movement "inverse movement parallax", but I have not used this term because there is in fact an absence of retinal movement parallax in a stereoscopic figure. He suggests that movement is perceived because "the binocular disparity changes". The types of disparity change that occur are considered in the "Discussion", reaching the opposite conclusion that movement occurs not because the disparity changes, but because the change in perceived depth is not sufficient to conform to the observer's expectations.

The question arises whether the movement is due to some feature of the retinal image changes alone or whether kinaesthetic information from head and body movements is required to see the induced movement. A simple test can be made by tilting the anaglyph horizontally back and forth about its vertical axis. This produces the same relative movement between the head and the anaglyph but with the head stationary. The result is that in addition to the tilt of the figure, the induced relative shift of the stereoscopic planes is still clearly observed. The effect therefore does not depend upon kinaesthetic feedback.

If the anaglyph is viewed at a rotation of 90°, so that the vertical rather than horizontal disparity is produced, there is no perception of depth and also no induced movement. The effect thus requires depth processing of the disparity changes. On the other hand, induced movement is readily seen with a vertical stimulus tilt about the horizontal axis, or a vertical head movement. It therefore cannot result from small asymmetries in the effect of the tilt in each eye, since a vertical tilt has a symmetrical effect on the two eyes. Analysis of the geometry of induced stereomovement can therefore be restricted to the changes in the cyclopean image rather than the two monocular half-image characteristics (Lee, 1969).

The cues for tilt-induced stereomovement may be described in terms of the interaction of real and artificial stereoscopic information (Fig. 1). When the anaglyph is tilted from the fronto-parallel plane retinal disparity at each point is the sum of the real disparity produced by the tilt and the artificial disparity of the random-dot correlations, the latter being essentially affected only by the contraction of the elements resulting from tilting the anaglyph. Strictly, the disparity changes are proportional to sin θ, where θ is the angle of tilt, whereas the contraction in visual angle of the same image (and hence the change in artificial disparity) is proportional to cos θ. For small angles sin $\theta \simeq \theta$ and cos $\theta \simeq$ constant. The relationships hold within 1 per cent for the angles up to 6°, the largest used in the threshold experiments described. This small deviation is negligible in relation to the best discrimination of disparity differences, which is about 5 per cent by interpolation from the data of Blakemore (1970). Thus the proximal stimulus for induced stereomovement is essentially from the addition of disparity change produced by real tilt movement to the artificial disparities of the stereoscopic figure. The artificial disparity is negligibly affected by contraction of the retinal image size during tilt in the range investigated.

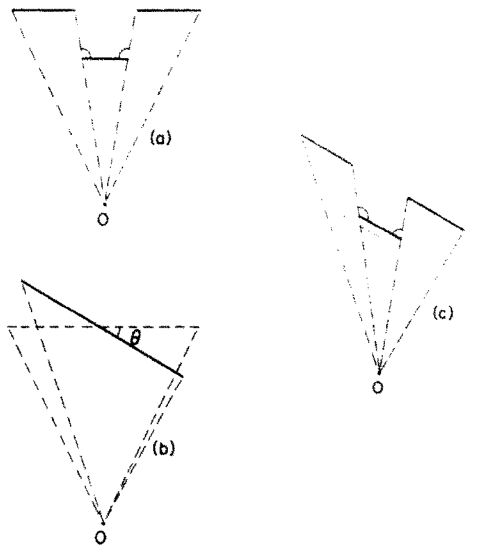

Fig. 1. Cyclopean depiction of distortion produced by tilting a simple anaglyph viewed at 0. (a) Artificial depth of anaglyph. (b) Real depth produced by tilt of angle θ. (c) Sum of real and artificial disparities produces distortion of the cyclopean figure with relative shifting of the initial fronto-parallel planes.

The present experiment was designed to compare the sensitivity for induced stereomovement with that for tilt of the anaglyph viewed stereoscopically or monocularly, using sinusoidal oscillation in tilt over a range of frequencies. It has already been shown that sensitivity for single line stereomovement is reduced relative to that for the monocular components of the stereomovement stimulus (Tyler, 1971). This reduction implies that the stereoscopic system suppresses some monocularly available movement information, and therefore involves further neural processing than monocular movement perception. If induced stereomovement can be perceived as readily as the tilt stereomovement that is inducing it, one must conclude that the characteristics of the induction process are undetectable by the present method. If, on the other hand, sensitivity for induced stereomovement differs from that of tilt stereomovement, the difference should give some indication of the nature of the neural processing involved in the induction. The results of Liebowitz *et al.* (1954) suggest that the induction process for three-dimensional shape constancy is relatively slow. This leads to the prediction that if induced stereomovement involves the operation of shape constancy, it should show a reduction in sensitivity at high oscillation frequencies. The null hypothesis is that sensitivity for all types of movement will be the same at all frequencies.

METHOD

The anaglyph was mounted on a pen-motor so as to rotate about a vertical axis. The pen-motor was driven by a low frequency Wavetek oscillator. The anaglyph was taken from Julesz and Johnson (1968) and contained a complex stepped-pyramid figure to provide optimal movement cues. It was viewed by two subjects through red–green spectacles and with normal optical correction. The entire stimulus subtended 12° at the eye, viewed from a distance of 40 cm against a uniform white background of approximately the same luminance. Each step of the pyramid subtended 0·5°. Its average luminance was 1·5 ft-L viewed through the red filter and 2·2 ft-L through the green filter.

The basic experiment was to compare sensitivity to sliding of the planes in the anaglyph (induced stereomovement) with the visibility of anaglyph rotation (tilt stereomovement). In addition, two control conditions were measured. The first was monocular sensitivity to movement in the anaglyph, viewed through either the red or green filter. The second was a test that the apparent extension in depth of the stereoscopic figure did not change. If a rapid oscillation of the anaglyph reduced the visibility of the figure, it would be likely to affect sensitivity to induced stereomovement in that figure, which would tend to zero when the figure became invisible. The apparent extension was therefore measured by means of a movable pointer which the subject set to match the maximum depth of the figure while it oscillated at the greatest extent used in the threshold measurements.

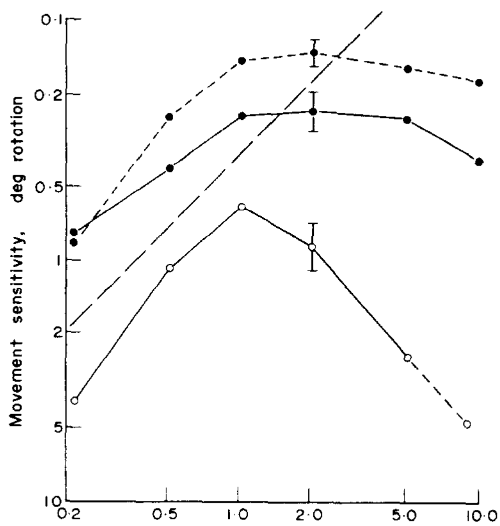

Fig. 2. Threshold sensitivity to three types of movement as a function of frequency of oscillation of a random-dot stereogram (Subject CWT). Ordinate shows rotation of the stereogram in degrees on reciprocal logarithmic coordinates to indicate sensitivity. Dashed line, filled circles—monocular observation. Full line, filled circles—stereoscopic observation using a criterion of any visible movement. Full line, open circles—stereoscopic observation using a criterion of induced stereomovement (see text). Dashed line—slope of unity.

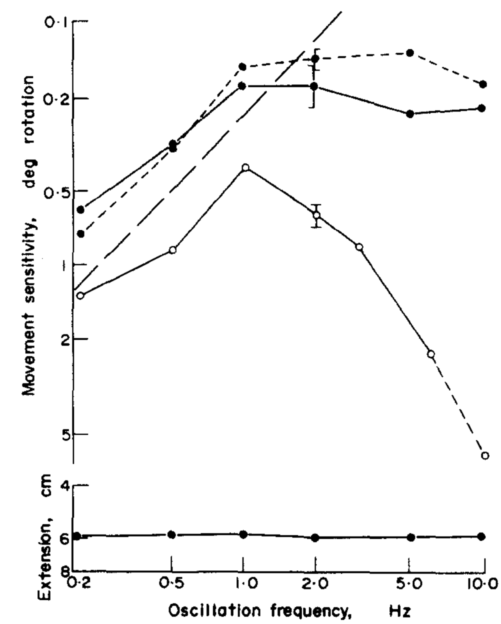

Fig. 3. Upper portion—replication of Fig. 2 for subject BB. Lower portion—apparent extension of stereogram figure at greatest extent of oscillation as a function of frequency.

The subjects were instructed to fixate the centre step of each side of the pyramid switching back and forth during each threshold determination. This procedure reduced any possibility of stereoadaptation (Blakemore and Julesz, 1971). The subject adjusted the amplitude of oscillation of the anaglyph until the criterion movement was just invisible. He followed this procedure for each of the four movement criteria (right monocular, left monocular, tilt stereomovement and induced stereomovement) selected in random order for one frequency. The set was then repeated for the other five frequencies, selected in random order. The whole design was then rerandomized and replicated to give two readings in each condition, which were sufficient to establish the effects of interest. The apparent extension of the figure was measured in a separate session, taking two settings at each frequency in random order.

RESULTS

Sensitivity (reciprocal of threshold setting) for each movement criterion as a function of oscillation frequency is plotted on double logarithmic coordinates (Figs. 2 and 3). The results are consistent for the two subjects. Greatest sensitivity of about 9′ rotation was obtained for monocular observation at higher frequencies, the red and green filter data being combined for simplicity (dashed line). Note that 10′ of rotation of the stereogram will produce up to 4″ arc shift of the monocular retinal image aroung the point of fixation. This value is of the same order as previously obtained sinusoidal movement thresholds (Tyler, 1971).

The maximum depth of the overall cyclopean figure was measured for one subject (open squares, filled circles, Fig. 3) at 10° oscillation. The variability of the measurements is less than the height of the symbols. There is no change in the maximum depth over the frequency range used in the experiments, so it cannot be a factor in changes of induced stereomovement sensitivity.

The maximum amount of movement information in binocular viewing should be the sum of the monocular sensitivities, since to the extent that the rotation of the anaglyph approximates movement toward and away from the observer in the median plane, the movement is in the opposite direction in the two eyes. However, measurement of stereomovement sensitivity (full line) shows that it is never significantly greater than the mean monocular sensitivity and at higher frequencies it is reduced by about 0·2 log units. This indicates that the stereomovement suppression previously reported for single line stimuli (Tyler, 1971) occurs also using a complex stimulus pattern and a complex movement configuration. One difference between the two sets of results is that the suppression of stereomovement in the anaglyph seems to disappear at low frequencies. A similar effect has been found for the single line stimuli when the reference line moves sinusoidally in antiphase with the moving line (Tyler, unpublished). Since there is antiphase stereomovement in the rotation of the anaglyph, it is not surprising that it shows a sensitivity similar to the antiphase line stereomovement rather than to the stationary reference line condition.

Sensitivity for the shifting planes of induced stereomovement (open circles in Figs. 2 and 3) is lower again than that for binocular movement. In the low frequencies the two sensitivities have a similar form, with induced stereomovement lower by about 0·4 log units. The similarity of frequency dependence below 1 Hz for all three movement criteria suggests that they all may be limited by the same factor. The slope of the functions approximates a slope of 1 (dashed line). This slope corresponds to the change in threshold that would occur if sensitivity was set by the maximum velocity in the sinusoidal oscillation, rather than its maximum displacement.

At high frequencies, sensitivity for induced stereomovement is reduced to more than 1 log unit lower than that for tilt stereomovement. (The last point could only be determined to a minimum value, so it is connected by a dotted line to indicate the least slope that could actually have occurred.) This represents a reduction in the ability to perceive the rigidity of the stereoscopic object at high rates of movement, and supports the conclusion of Leibowitz *et al.* (1954) that shape constancy is reduced at short exposure durations since the high frequency may be regarded as a succession of brief exposures at different rotations.

DISCUSSION

How can induced stereomovement be abstracted from the tilt movement information? I suggest that shape constancy may be operating in that images of three-dimensional rigid objects are expected to undergo certain transformations when tilted, such that the objects have a fixed shape. This explanation implies that the subject has the perceptual hypothesis that different parts of the lower planes should come into view during the tilt, but this does not occur. The contradiction is reconciled in seeing the two planes sliding relative to each other.

Hay and Sawyer (1969) and Gogel and Tietz (1973) find that when an object is perceived as lying at a distance from the observer other than its actual distance, either by convergence or perceptual factors, movement of the observer's head induces apparent movement of the object. Any change in the error in perceived distances of two objects present simultaneously would result in an apparent relative motion of the objects. This movement parallels the induced size change noted previously (Tyler, 1971) in line stimuli of fixed retinal size when binocular disparity is varied. This is a special case of Emmert's size-distance invariance (Boring, 1942) when the relative distances are determined by disparity rather than other types of distance cues.

A more complex process must underlie the perception of rigidity and plasticity in real objects. We are able to perceive that a person's arm moves if he keeps pointing at us when we walk past, although the retinal images hardly change and the distance is perceived appropriately. The experiment reported here demonstrates that perception of movement induced by three dimensional shape constancy is a relatively slow process, and thus requires much stronger stimulation (larger disparity changes) to reach threshold at frequencies above about 1 Hz. A corresponding observation can be made when running or walking upstairs. In the fast phases of the body and head movement, objects at different distances appear to jump up and down, whereas during slow phases objects are observed to maintain a roughly constant relationship, i.e. the movement can be referred to the observer and object shape constancy is maintained. This inability to follow induced stereomovement at the higher frequencies suggests that it involves extra stages of processing beyond those required for tilt stereomovement.

It is worth asking whether induced stereomovement is processed at the same level as the most complex stereoscopic movement previously investigated, i.e. global stereopsis, or whether it requires still further processing. This question can be answered if sensitivity for induced stereomovement differs from sensitivity for movement existing only at the level of global stereopsis. It has not been possible to investigate the question directly, but Julesz and Payne (1968) reported that the optimal frequencies for global apparent stereomovement are 3–4 Hz, about 1 Hz less than the optimal frequencies for molecular apparent movement. In contrast, induced stereomovement peaks at 1 Hz and is considerably reduced by 5 Hz. This discrepancy is evidence that induced stereomovement requires more processing time than global stereomovement, in accord with the suggestion that a complex process such as three-dimensional shape constancy is involved in the generation of induced stereomovement.

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Résumé—On étudie les limitations temporelles de la constance de forme à trois dimensions en mesurant la perception de mouvement d'un stéréogramme oscillant à points au hasard. L'écart à la constance de forme produit par ce stimulus induit un mouvement apparent de la figure stéréoscopique. Ce stéréomouvement induit est perçu au mieux à de basses fréquences d'oscillation. La perception du stéréomouvement induit diffère de la perception monoculaire de mouvement et des types précédemment observés de stéréomouvement.

Zusammenfassung—Die zeitlichen Grenzen der dreidimensionalen Gestaltkonstanz wurden durch Messung der wahrgenommenen Bewegung in einem oszillierendem Punktraster-Stereogramm untersucht. Abweichungen von der Gestaltkonstanz ergeben bei diesem Reizmuster Scheinbewegungen in der stereoskopischen Figur. Diese induzierte Stereobewegung sieht man am besten bei niedrigen Oszillationsfrequenzen. Die Wahrnehmung der induzierten Stereobewegung unterscheidet sich von der Wahrnehmung einer monokularen Bewegung oder schon früher beobachteten Arten von Stereobewegungen.

Резюме—Временные лимиты константности трехмерной формы были ис-следованы путем измерения восприятия движения в осциллирующей стереограмме, состоящей из тоуек расположенных в случайном порядке. Отклонение от Эонстантности формы, вызываемое зтим стимулом, индуцрует кажущееся движение в стереоскопическом рисунке. Зто стерео= движение лучше воспринималось при низких частотах осцилляций. Восприятие индицированного стеродвижения отличается от восприятия монокулярного движения или ранее наблюДавшихся типов стереодвижения.