



# Abnormal depth perception from motion parallax in amblyopic observers

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## Abstract

Many similarities exist between the perception of depth from binocular stereopsis and that from motion parallax. Moreover, Rogers (1984, cited in, Howard, I. P., & Rogers, B. J. (1995). *Binocular vision and stereopsis*. Oxford Claridon, New York.) suggests a relationship between an observer's ability to use disparity information and motion parallax information in a depth perception task. To more closely investigate this relationship, depth perception was studied in normal observers and amblyopic observers with poor stereo vision. As expected, amblyopic observers performed much worse than normal observers on depth discriminations requiring use of binocular disparity. However, amblyopic observers also performed much worse than normal observers on depth discriminations based on motion parallax. This result provides supporting evidence for a psychoanatomical link between the perception of depth from motion and the perception of depth from binocular disparity. © 1999 Elsevier Science Ltd. All rights reserved.

*Keywords:* Motion parallax; Depth perception; Amblyopia

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## 1. Introduction

Depth perception is of undeniable importance for quick and effortless locomotion through a cluttered and hazard-filled environment. To this end, the visual system uses numerous sources of information for depth perception. Of all possible depth cues, binocular stereopsis and motion are perhaps the two most important. Both cues are well known to generate a vivid sense of depth (Helmholtz, 1909) through the use of a spatial or temporal optical parallax cue (Gibson, 1950).

Of these depth cues, most is known about binocular stereopsis (Julesz, 1971; Howard & Rogers, 1995). Binocular stereopsis relies on the interocular differences or disparities in the position of image contours falling on the retinae. The neural mechanisms by which this binocular retinal disparity is encoded by the visual system have received a great deal of study (Ohzawa, DeAngelis & Freeman, 1996, 1997). In contrast, much less is known about the processing of motion parallax information and some have even suggested that motion

parallax is an ineffectual cue to depth (Epstein & Park, 1964; Gogel, 1977). However, using random-dot stimuli, Rogers and Graham (1979) have convincingly demonstrated that observers can accurately perceive depth from motion parallax. Unfortunately, neural mechanisms for depth from motion parallax are less well understood than those used for binocular stereopsis. For example, Nawrot and Blake (1991b) have suggested that depth from motion is processed in a network of disparity and motion selective units, although this model fails to account for the unambiguous depth perceived with motion parallax.

Despite the inherent stimulus differences between binocular stereopsis and motion parallax, there is much evidence for close processing ties between binocular stereopsis and motion parallax. Rogers and Graham (1982, 1983) have found that the two cues provide very similar depth sensitivity and that this depth sensitivity shows similar variations with orientation for both binocular stereopsis and motion parallax. Additionally, Graham and Rogers (1982), Rogers and Graham (1984) have shown interactions between binocular stereopsis and motion parallax in the form of perceptual aftereffects. More generally, links between depth

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from stereopsis and depth from motion are numerous. Tittle and Braunstein (1993) have shown additive effects of stereopsis and motion in depth perception while Rogers and Collett (1989), Bradshaw and Rogers (1996) and Nawrot and Blake (1991a,b, 1993a,b) have demonstrated numerous interactions between motion and binocular stereopsis in the perception of depth. Together these studies present compelling evidence that binocular stereopsis and motion parallax share a common neural process for depth perception.

Perhaps the most interesting evidence for a link between binocular stereopsis and depth from motion comes from studies comparing observers' relative abilities for using these two cues. Richards and Leiberan (1985) found a significant relationship between observers' perception of depth from binocular stereopsis and their perception of depth from motion. In particular, these investigators found that observers' depth discrimination abilities in convergent disparities were significantly correlated with each observer's perception of depth from motion. Although the precise implications are unclear (Bradshaw, Frisby & Mayhew, 1987), these results again suggest an important link between an observer's perception of depth from stereo and motion.

Along these same lines, Rogers (1984) (reported in Howard and Rogers (1995)) found a relationship between normal observers' thresholds for motion parallax and for binocular disparity. Although Rogers' original data (Howard & Rogers, 1995) show only a weak correlation (approximately  $r = 0.27$ ,  $P = 0.38$ ), the exclusion of two outliers with extraordinarily high stereo thresholds (each more than double the mean of the remaining group) results in a significant correlation (approximately  $r = 0.62$ ,  $P = 0.04$ ) between stereo and motion parallax thresholds. That is, analysis of the 11 most clustered observers reveals a significant correlation between stereo depth thresholds and motion parallax thresholds. If this were indeed the case, one might expect that a group of observers with poor stereo vision would also perform poorly on a motion parallax task while a group with normal stereo vision would perform much better on a motion parallax task. Such a result would support a psychoanatomical link between binocular stereopsis and motion parallax (Blake, 1995).

However, an equally likely alternative might be termed a compensation hypothesis (Howard & Rogers, 1995). This compensation hypothesis predicts that observers with poor stereo vision compensate for this depth perception deficit with improved motion parallax abilities. If this were the case, the group of observers with poor stereo vision would perform equal to or better than the group of normal observers. The study presented here was designed to determine which of these two hypotheses is correct.

To further study a possible link between binocular stereopsis and motion parallax, we examined the stereo

and motion abilities of two groups of observers. Whereas Rogers (1984) studied a group of normal observers whose stereo abilities lay along a continuum, we compared the performance of a group of normal observers to the performance of a group of strabismic amblyopes with poor stereo vision. If there is a common processing link for binocular stereopsis and motion parallax, the group of observers with poor stereo vision should perform poorly on a motion parallax task. However, if the compensation hypothesis is correct, the group with poor stereo vision will perform normally on the motion parallax task.

## 2. Methods

### 2.1. Participants

Ten strabismic amblyopic observers (two observers were also anisometric) with poor stereo vision were identified and recruited through a subject pool screening questionnaire given to over 1200 introductory psychology students. Observers answering strongly affirmatively to questions about amblyopia, stereo vision anomaly, and a willingness to participate in this research for course credit were approached to participate in this study. A brief history was taken from each amblyopic observer. Normal control observers were also recruited from the same subject pool.

Preliminary visual screening was performed with several standardized tests. Monocular function was assessed with a 10 ft acuity chart and the Peli-Robson contrast sensitivity chart illuminated at 85 cd/m<sup>2</sup> (Clement Clarke, Columbus, OH). Normal observers were required to have a minimum Snellen monocular acuity of 20/40, and a minimum log contrast sensitivity of 1.50. The amblyopic observers were required to meet the same standards in their best eye (which would later be used in the monocular motion parallax test). Stereoscopic visual function was assessed with the Randot and Stereofofly tests (Stereo Optical Company, Chicago, IL). Normal observers could have a stereo threshold no less than 60 s in each test. Amblyopic observers could have a threshold no better than 200 s in each test, thereby insuring that they truly had a deficit in stereo vision.

### 2.2. Stimuli

Depth perception thresholds for both stereopsis and motion parallax were determined with a random dot stimulus modeled on that used by Rogers and Graham (1982). The stimulus in both conditions depicted a horizontally oriented undulating corrugated surface. The stimulus had a corrugated sinewave profile of 0.4 cpd, which is in the range of peak sensitivity found by

Rogers and Graham (1982). The stimuli were created from 2500 randomly positioned ( $1 \text{ min}^2$ ) black dots presented against a white background. The corrugations were positioned so that zero relative depth was found at a horizontal line across the center of the screen so that a peak might protrude above this line, a valley recede below this line, or vice versa. A small fixation point was provided on this line so that observers did not scan the stimulus during trials. The entire stimulus subtended  $2.2 \text{ deg}^2$ .

The stereoscopic version of this sinusoidal stimulus was generated by assigning dots at the corrugation peaks the maximum crossed disparity and corrugation valleys the maximum uncrossed disparity. The disparity of dots along the slope in between were assigned disparity contingent on their position along the slope. Greater perceived depth is found with greater maximum disparity used in the stimulus. Binocular separation was achieved with the frame sequential method using LCD goggles synchronized to the refresh rate of the screen and driven through the serial port on the computer. Stereoscopic stimuli were viewed at a distance of 342 cm, allowing one full cycle of the sinusoidal stimulus to be shown and a minimum disparity value of 20 s.

A linear head movement device was used to generate depth from motion parallax with this same random-dot stimulus type. A chin rest was mounted on linear bearings on a pair of steel rails. The chin rest moved laterally along the horizontal ( $X$ ) axis effortlessly for a full excursion of 13 cm. Chin rest position was monitored with an attached linear potentiometer (ETI Systems, Carlsbad, CA) connected to the computer system

through an ADC card (National Instruments, Austin, TX). This head movement system had a resolution of 0.1 mm of movement and a linearity of  $r^2 = 0.9999$ .

To create a motion parallax stimulus, the computer monitored chin rest position. When the chin rest moved to the right, dots at the peak of the corrugation were translated maximally to left while dots at the corrugation valleys translated to maximally the right (Fig. 1). Dots along the slope were translated an amount proportional to each position along the corrugation in depth. Greater perceived depth is found with greater maximum translations within the stimulus, similar to the effect of binocular disparity. Indeed, the quantification of the motion parallax stimulus is in terms of disparity equivalence (Rogers & Graham, 1982), the amount of stimulus dot movement created with a movement equivalent to a head movement of the interocular distance. For all computations we used a fixed value of 6.5 cm which approximates the interocular distance (Cormack & Fox, 1985).

Observers viewed this motion parallax display from 114 cm. With this shorter viewing distance, the monitor was capable of displaying three complete cycles of the 0.4 cpd sinusoidal surface, now composed of 7500,  $1 \text{ min}^2$  dots. This increase in dot number preserved the dot density of the stimulus surface, and this high dot density is believed to improve the perceived depth in such displays (Szatmary, Hadini & Julesz, 1997). The entire stimulus now subtended  $6.7 \text{ deg}^2$ .

Stimuli were presented on a monochrome monitor controlled by a Macintosh computer system. The contrast of the monitor was essentially 100% with the

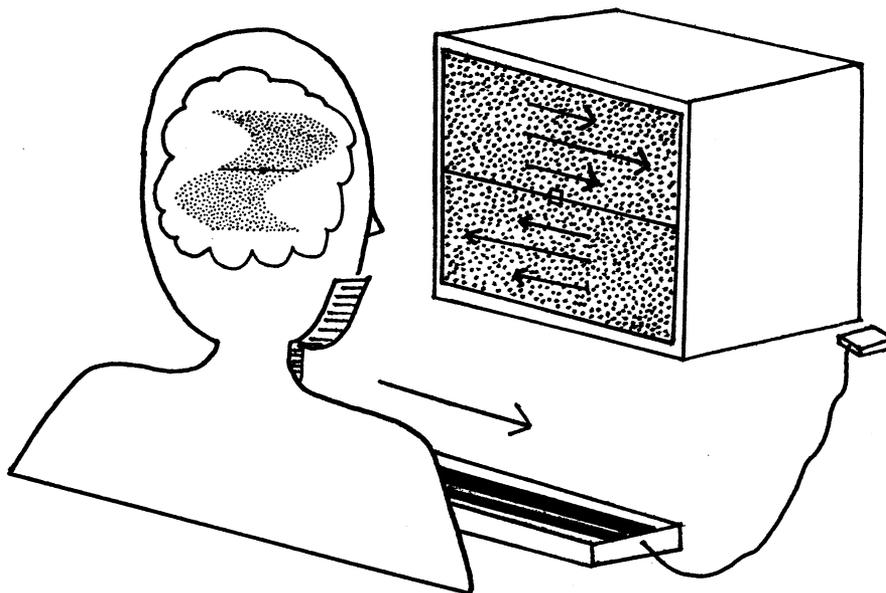


Fig. 1. Schematic of the experimental apparatus for motion parallax. The observer's head position was monitored with a linear potentiometer and an analog to digital converter. Changes in head position were translated into changes in dot position so that the observer perceived a dot covered surface with corrugations in depth.

Table 1  
Screening results for amblyopic observers

Subject	Snellen acuity		Log contrast sensitivity		Randot (s)	Stereofly (s)	MP test eye
	RE	LE	RE	LE			
1	20/40	20/16	1.80	1.95	>400	200	Left
2	20/20	20/25	1.95	1.95	>400	800	Right
3	20/125	20/16	1.80	1.95	>400	200	Left
4	20/16	20/60	1.80	1.65	>400	>800	Right
5	20/25	20/25	1.80	1.80	400	400	Right
6	>20/160	20/20	0.15	1.50	400	200	Left
7	20/20	20/30	1.80	1.65	200	400	Right
8	20/16	20/20	1.80	1.65	400	400	Right
9	20/20	20/30	1.65	1.65	400	400	Right
10	20/20	20/30	1.65	1.65	400	400	Right

The greater sign (>) indicates that the observer was unable to perform the task at the limit of the test.

luminance of the white background set to 3.0 cd/m<sup>2</sup> and the luminance of the black dots set immeasurably low as measured with a luminance meter (Tektronics: Beaverton, OR).

### 2.3. Procedure

Thresholds in both the stereopsis and motion parallax conditions were determined with a staircasing procedure using the Up-Down-Transformed Response Rule (UDTR) (Wetherill & Levitt, 1965; Macmillian & Creelman, 1991; Brown, 1996). Tracking towards a 79.4% correct threshold value, this procedure required three consecutive correct responses at a particular level of the independent variable (i.e. disparity or amount of depth portrayed by the stimulus) before decreasing the value of the independent variable. A single incorrect response increased the value of the independent variable (i.e. larger depth). In both conditions the observer's task was to report which part of the stimulus (upper or lower) appeared to recede away (far relative depth), using the fixation point and the horizontal line across the stimulus as a reference for this decision.

In the stereopsis condition, the staircase began with 500 s of disparity, moved in 20 s steps, and operated with a ceiling of 1000 s and a floor of 20 s disparity. In the motion parallax condition, the staircase began with 600 s of disparity equivalence, moved in 60 s steps, and operated between a ceiling of 1020 s and a floor of 30 s disparity equivalence. Ceiling values were set where diplopia and the perception of dot movement began to occur suggesting useful limits of this computer generated stimulus design. Floor values were set at the limit of the experimental apparatus. The staircase procedure ended after 13 reversals, and the threshold value was calculated from the mean of the last ten reversals. However, if the staircase reached either the ceiling or floor value, the threshold was assigned that corresponding value.

Observers viewed the stimuli while seated in a darkened room. In the stereoscopic condition observer head position was fixed by a stationary chin rest. Observers viewed the stimulus binocularly through LCD goggles. In the motion parallax condition observer head position was free to move laterally within the range of the chin rest moving on rails. Observers viewed this stimulus monocularly with one eye covered by a patch. Both normal and amblyopic observers used their best or preferred eye for viewing: the affected eye of amblyopic observers was not used in the motion parallax task. Observers initiated trials and made responses with a keypress. Stimulus viewing time was unrestricted, although most responses were made within a few seconds.

## 3. Results

### 3.1. Screening tests

Preliminary screening results for the ten amblyopic observers are shown in Table 1. All ten of these observers had poor stereoscopic vision indicated by thresholds of 200 s or more. However, at least one eye from each amblyopic observer was essentially normal in acuity and contrast sensitivity. Table 2 shows the median values for both amblyopic and normal observer groups. The 'best eye' was that used in the motion parallax task. From this comparison it should be apparent that (1) normal observers performed well on stereo screening tests while the amblyopic group did not; and (2) the 'best eyes' of the two groups were very closely matched in both acuity and contrast sensitivity. Therefore, the amblyopic and normal groups differed in stereo vision and should therefore exhibit a threshold difference in the computerized stereo test. However, as the 'best eyes' were essentially identical in the two observer groups, any difference between groups in the motion parallax

condition is not explained by a simple difference in monocular vision.

### 3.2. Stereo and motion parallax tests

Normal observers performed very well in both the stereo and motion parallax conditions. Eight and nine of the observers reached the staircase floor in the two tests, respectively. As expected, the amblyopic observers performed poorly in the stereo condition (six observers at ceiling). This is not surprising as the inclusion criteria for these observers was poor stereo vision. However, these observers also exhibited poor performance in the motion parallax condition with eight of the observers reaching the staircase ceiling. Only one of the amblyopic observers had a motion parallax threshold approaching that of the normals (2.8 min disparity equivalence). Amblyopic observers reported problems determining depth order in both conditions. Additionally, most amblyopic observers reported seeing a combination of depth and dot movement in the motion parallax condition while the normal observers reported little or no dot movement.

As the median values for each group/condition represent the staircase floors and ceilings, the mean threshold values for the amblyopic and normal groups on the stereo and motion parallax tests are shown in Fig. 2. A repeated measures analysis of variance reveals a significant main effect of observer group (normal vs. amblyopic),  $F(1, 18) = 246.09$  ( $P < .001$ ), no effect for type of test (stereo vs. motion parallax),  $F(1, 18) = 0.10$  ( $P > 0.05$ ), nor an interaction (observer group  $\times$  test),  $F(1, 18) = 0.09$  ( $P > 0.05$ ). Of course, the staircase ceiling and floor served to reduce within group variability and perhaps eliminate any possible difference between the two tests. But the main point is obvious: amblyopic observers performed much worse than normals on a test of motion parallax. These results suggests that there is a relationship between stereo and motion parallax performance. These results are also contrary to those predicted by the compensation hypothesis (Howard & Rogers, 1995).

## 4. Discussion

The interpretation of this study hinges on one result: amblyopic group performance in the motion parallax

condition. As expected, normal observers performed very well in both the stereo and motion parallax conditions and the amblyopic group with poor stereo vision performed poorly in the stereo condition. The performance of the amblyopic group in the motion parallax condition was the only real question and it turns out they performed poorly in this condition. However, this general pattern of results allows one alternative hypothesis: perhaps normal observers learned something about performing the motion parallax task by first successfully performing the stereo task. The amblyopic observers would not have had this opportunity due to their stereo vision problems and their lack of success in the stereo condition. To address this alternative explanation, a group of ten normal observers was screened and tested on the motion parallax test, without first performing the stereo condition. These normal observers had no difficulty with the motion parallax test with a mean threshold of 1.6 min disparity equivalence (compare to 1.2 min shown in Fig. 2). Therefore, prior stereoscopic viewing of the stimulus is not necessary for good performance on the motion parallax task.

Currently it is unknown whether this motion parallax deficit is specific to amblyopes with a developmental deficit in stereo vision, or whether this deficit would be found in other observers with abnormal stereo vision. Initial evidence suggests that abnormal stereo developmental might be an important factor. Larson and Simonet (1992) reported preserved depth perception from motion parallax in an observer with one blind eye. This observer lost vision in one eye due to a corneal injury at the age of 7 years, presumably after a normal development. For the current study, we identified and recruited amblyopic observers only to achieve a homogeneous observer group exhibiting stereo vision problems. We certainly acknowledge that other factors of the amblyopic condition make these observers ideal candidates to study the relationship between depth from stereo and depth from motion.

There is growing evidence for a motion processing deficit in amblyopia. For instance, several studies have reported some form of abnormal motion perception in amblyopia (Schor & Levi, 1980; Levi, Klein & Aitsebaomo, 1984; Tychsen & Lisberger, 1986; Steinman Levi & McKee, 1987; Hess and Anderson, 1993). Additionally, strabismic amblyopes experience reduced motion aftereffect (MAE) in the amblyopic eye and poor interocular transfer of the MAE (O'Shea, McDonald,

Table 2  
Comparison of normal and amblyopic group medians

	Best eye acuity	Best eye log contrast sensitivity	Randot	Stereofly
Amblyopes	20/20	1.80	400"	400"
Normals	20/16	1.80	20"	40"

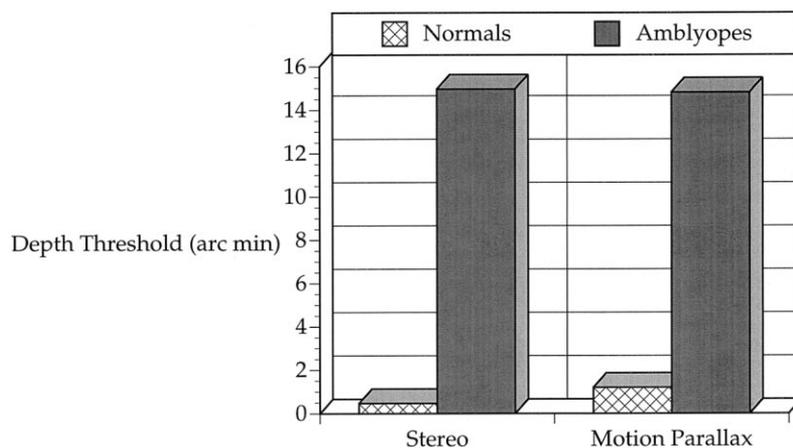


Fig. 2. The mean depth threshold values for the two groups in the stereo and motion parallax tests are given in terms of arc min retinal disparity (stereo) and arc min disparity equivalence (motion parallax). Normal observers performed well in both conditions while amblyopic observers performed poorly in both conditions.

Cumming, Peart, Sanderson & Molteno, 1994; Hess, Demanins & Bex, 1997). However, because the MAE is essentially normal in the unaffected, or fellow, eye in these amblyopic observers, the implications for the current study remain unclear (recall that our amblyopic observers used their fellow eye to perform the motion parallax task).

Perhaps more closely related is Giaschi, Regan, Kraft & Hong (1992) evidence for defective processing of motion defined form in amblyopia. This deficit was seen in both the amblyopic and fellow eyes of these observers. This further supports a cortical basis for a motion processing deficit, which may account for the poor interocular transfer of the MAE in amblyopic observers. This same cortically based motion processing deficit might also be involved in the motion parallax deficit shown here.

Clearly, the current results indicate that amblyopic observers with poor stereo vision do not have normal depth perception from motion parallax. As amblyopic observers display both stereo and motion parallax deficits, the most parsimonious explanation invokes an integrated neural processing mechanism for binocular stereopsis and motion parallax. If this mechanism is compromised, as we assume it is in our stereanomalous observers, the effects are also seen in motion parallax conditions. Considering the myriad evidence for connections between motion and stereopsis, it is unlikely that the stereo and motion parallax deficits arise independently. Indeed, many neurons in visual cortex are simultaneously selective to both binocular disparity and motion (Regan & Beverley, 1973; Poggio & Talbot, 1981; Maunsell & Van Essen, 1983; Roy, Komatsu & Wurtz, 1992), a property that has been previously used to model and explain interactions between binocular

disparity and depth from motion (Nawrot & Blake, 1991a,b).

One distinct problem is that we do not yet know or understand all of the important psychophysical and neural elements for the perception of depth from motion parallax. For instance, the role of viewing distance is still unknown. Ono, Rivest and Ono (1986) found depth from motion parallax scaled with viewing distance at 40 and 80 cm, but not at 160 and 320 cm viewing distance. In subsequent testing with our amblyopic group, we found that four of the ten observers improved their performance on the motion parallax task when the viewing distance was halved to 57 cm. In this case, these observers reported seeing some depth and little dot movement (Ono & Steinbach, 1990).

This last result is reassuring in that amblyopic observers do have some ability to use motion parallax information for depth perception, although their thresholds are much higher than those of normal observers. Perhaps even this reduced use of motion parallax is sufficient for fast and efficient navigation in a cluttered environment. However, the problem still remains for us to learn more about the mechanisms of motion parallax so that we might better understand the deficit described here.

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