# Depth from motion parallax scales with eye movement gain

**Mark Nawrot**

Department of Psychology, North Dakota State University, Fargo, North Dakota, USA

Recent findings suggest that the slow eye movement system, the optokinetic response (OKR) in particular, provides the extra-retinal signal required for the perception of depth from motion parallax (Nawrot, 2003). Considering that both the perception of depth from motion parallax (Ono, Rivest & Ono, 1986; Rivest, Ono & Saida, 1989) and the eye movements made in response to head translations (Schwarz & Miles 1991; Paige, Telford, Seidmen, & Barnes, 1998) appear to scale with viewing distance, changes in perceived depth from motion parallax were studied as a function of viewing distance. If OKR is used in the perception of depth from motion parallax, a change in the OKR signal, caused by a change in viewing distance, should accompany a change in perceived depth from motion parallax. Over a range of viewing distances, binocular stereopsis was used to index perceived depth from motion parallax. At these viewing distances the gain of the OKR portion of the compensatory eye movement was also determined. The results show that the change in OKR gain is mirrored by the change in perceived depth from motion parallax as viewing distance increases. This suggests that the OKR eye movement signal serves an important function in the perception of depth from motion.

Keywords: motion, depth, motion parallax, eye movements, translational vestibular ocular response

## Introduction

Our perception of depth in a three-dimensional world relies on the visual system's interpretation of the information from our two-dimensional retinal surface. While many different depth cues have been enumerated, binocular stereopsis and motion parallax are arguably the most important. Binocular stereopsis uses the slight differences in the images falling upon the two retina, known as binocular disparity (BD), to recover depth information. The stimulus conditions for motion parallax (MP) are created when an observer translates while viewing a rigid environment. While the observer's fixation is automatically maintained on a specific point, objects nearer or farther than the fixation point move relative to each other on the observer's retina. The visual system uses this relative movement of objects on the retina, motion parallax, as a cue to the relative depth of these objects in the environment. Observer movements may be abrupt lateral head translations or more sustained observer translations such as those generated when looking out the side window of a vehicle, a stimulus condition originally called motion perspective (Gibson, 1950).

Unlike binocular stereopsis, surprisingly little is known about the essential processing mechanisms necessary for MP. The role of head movement has been assumed to be of central importance (Steinbach, Ono & Wolf, 1991). Most recently, MP sensitivity has been quantified with regard to observer head translation velocity (Ujike & Ono, 2001) suggesting a primary role of head movement in the perception of depth from MP. However, there remains disagreement on whether head movement provides a required extra-retinal signal for the perception of depth from MP (Braunstein & Tittle, 1988; Rogers & Rogers, 1992).

In their original work demonstrating the importance of motion parallax as an independent depth cue, Rogers and Graham (1979) pioneered an experimental paradigm wherein shearing movement within a random-dot display was linked to translations of the observer's head parallel to the interaural axis. To an observer making a translational head movement, the stimulus appears to be stationary corrugated surface with peaks extending out from the computer monitor and valleys extending back into the monitor. When head movements and stimulus shearing motion both stop, no depth is perceived. Rogers and Graham (1979) also reported that the perception of depth was just as compelling, and unambiguous, with a fixed head when stimulus shearing movement was yoked to translation of the display monitor. Therefore, observer head movement does not appear to be a necessary condition for MP.

Recently, Nawrot (2003) proposed that the slow eye movement system provides the extra-retinal signal required for the unambiguous perception of depth from MP. This proposal recognizes that all the stimulus conditions creating MP have a single common demand that the observer's eyes move to maintain fixation on the stimulus. Using the Ono and Ujike (1994) motion aftereffect paradigm, Nawrot (2003) dissociated the roles of head movements, vestibularly driven eye movements – specifically the translation vestibulo-ocular response (TVOR) – and visually driven eye movements that will here be referred to as the optokinetic response (OKR). These visually driven eye movements could also be

doi:10.1167/3.11.17 Received May 2, 2003; published December 18, 2003 

considered smooth pursuit, or the early, direct phase of optokinetic nystagmus (OKNe) (see Miles & Busettini, 1992 for a review). Although these terms describe eye movements in response to slightly different stimulus conditions, the movements all share functional and physiological similarities and further study is undoubtedly required to understand their similarities or differences with respect to MP (e.g., Post & Leibowitz, 1985). Regardless of the specific terminology, Nawrot (2003) showed that these OKR eye movements provide the extra-retinal signal required for the perception of unambiguous depth from MP.

One important problem in understanding the perception of depth from motion parallax is understanding how MP scales with depth, otherwise known as depth constancy (see Howard & Rogers, 2002, Chapter 26 for a review). Similar to the perception of depth from binocular disparity, the perception of depth from MP appears to scale with viewing distance, or more specifically with apparent distance (Rivest et al., 1989). However, this scaling is quite imperfect in typical laboratory conditions causing Ono et al., (1986) to ask: "Why does the effectiveness of parallax decrease as a function of viewing distance?" Or, phrased in terms of depth constancy later in their paper, "Why does the compensation fail as the viewing distance increases?" That is, laboratory conditions for studying MP with side-to-side head movements appear to work best with short viewing distances. At larger viewing distances either no depth is perceived, or if depth is perceived it is ambiguous, fluctuates between reversing depth interpretations, and it shows no consistent relationship with the direction of observer head translation. For this reason most MP experiments in the literature include a viewing distance of 40 cm to 60 cm. Ono et al., (1986) is quite unusual in including viewing distances farther than 114 cm, and it was at these distances that they reported MP becoming less effective.

The link between OKR eye movements and motion parallax suggests a way to study the question of depth scaling in MP. Central is the consideration of the observer's head and eye movements occurring in tandem with the MP on the observer's retina. To maintain fixation during an abrupt lateral head movement, the eyes move in the opposite direction compensating for the head movement. The magnitude of the compensatory eye movement scales inversely with viewing distance. These compensatory eye movements typically have a gain very close to 1.0, relying on a combination of TVOR and OKR. Studies conducted in dark (non-visual) conditions show that the TVOR eye movement scales with the distance to the remembered or imagined fixation point, instead of remaining constant as you might expect of a response that occurs even in non-visual (dark) conditions (Schwarz et al., 1989; Bronstein & Gresty, 1988; Oas et al., 1992; Paige & Tomko, 1991; Paige et al., 1998). At near viewing distances, TVOR gain is typically less than 1 meaning that a large OKR component is required to maintain fixation. As viewing distance increases, TVOR gain approaches 1, meaning that smaller OKR eye movements are required with larger viewing distances. However, at much larger viewing distances TVOR gain is greater than 1 meaning that OKR eye movements must now suppress, cancel, or counteract the TVOR eye movements if fixation is to be maintained (Paige & Tomko, 1991). The current study investigates whether these changes in OKR with viewing distance are related to viewing distance changes in MP depth constancy.

One problem is how to measure a subjective experience such as perceived depth from MP. How does an observer report the magnitude of depth perceived in a specific condition? In the experiment presented here, the magnitude of depth perceived from binocular disparity (BD) is used to index the magnitude of depth perceived from MP. The most important reason for using this technique is that very similar visual stimuli can be used for both. Moreover, the two types of stimuli can be quantified in very similar ways. Binocular disparity may be quantified in terms of the difference in the horizontal angles subtended at the two eyes between an object point and the fixation point. Motion parallax is commonly quantified in terms of disparity equivalence (DE) that is the amount of local stimulus translation or displacement in the frontal plane for a head translation equal to the interocular distance, along the interaural axis. To compare MP and BD, an assumed interocular distance of 6.5 cm was used.

To model this comparison between BD and MP, we must consider the stimulus parameters that affect perceived depth. The distance-squared law, which specifies the relationships between these stimulus parameters (Cormack & Fox, 1985), provides a useful starting point. For the BD stimulus, the distance-squared law is:

$$d_S = (D_S^2 * \delta) / i \quad (1)$$

where $d_S$ is the specified depth, $D_S$ is the distance to the stimulus, $\delta$ is the binocular disparity, and $i$ is the inter-ocular distance. For the MP stimulus, the commonly used distance-squared law (Rogers & Graham, 1982) is:

$$d_M = (D_M^2 * \mu) / t \quad (2)$$

where $d_M$ is the specified depth, $D_M$ is the distance to the stimulus, $\mu$ is the disparity equivalence given by stimulus translation or displacement, and $t$ is the distance the head translated laterally. The psychophysical study described here will determine the disparity of the BD stimulus that generates perceived depth that matches the perceived depth in the MP stimulus; that is the stimulus parameters giving $d_S = d_M$. We can model this comparison of BD and MP by equating Equation 1 and Equation 2:

$$(D_S^2 * \delta) / i = (D_M^2 * \mu) / t \quad (3)$$

If all the variables in Equation 3 maintained the same relationships over changes in viewing distances, the perceived depths in the BD and MP stimuli would be equal when the specified parameters were equal. As the findings of Ono et al., (1986) tell us, this does not occur. So we have to consider which of the variables in Equation 3 might differ between the BD and MP stimuli.

In the experiment presented here, and in those by Ono et al., (1986), it is assumed that there is no systematic difference in the internal representation of viewing distance, $D_S$ and $D_M$. Such a difference is unlikely due to the unobstructed view of experimental apparatus. In the current study, the difference between BD and MP viewing was whether the observer's eyes were occluded sequentially by the shutter glasses (BD) or a single eye was briefly occluded (MP). Indeed, Bradshaw et al (1998, 2000) conclude from a BD and MP matching paradigm that BD and MP use "…the same estimate of viewing distance to scale size and depth estimates." If $D_S = D_M$, then they cancel in Equation 3 and do not explain the failure of constancy with motion parallax.

It is also assumed that there is no systematic difference in the perception of disparity and motion parallax, $\delta$ and $\mu$, over viewing distance Both parameters are quantified as proximal retinal stimuli, and the effect of viewing distance is only apparent when these proximal stimuli are used in the interpretation of depth. Moreover, the cue combination paradigm of Rogers and Collett (1989) suggests a very close perceptual equivalence for equivalent $\delta$ and $\mu$ parameters, at least when presented at a single 57 cm viewing distance. Therefore, if $\delta = \mu$, then they also cancel in Equation 3. (The reader should not confuse this theoretical equivalence in discussion of the distance-square law with the following study that uses a variable value of $\delta$ to match a standard value of $\mu$.)

Finally, since *i* (the observer's interocular distance) remains constant over changes in viewing distance, the only term in Equation 3 that can produce a difference in the perceived-depth matches as a function of viewing distance is *t*, the measured lateral translation of the head. Why might *t* be mis-estimated?

The hypothesis is that the effective *t*—meaning the internal parameter that affects the perceived depth in a MP display—is provided by the OKR eye movement signal. We have known since the original study by Rogers and Graham (1979) that head movements are not required for the unambiguous perception of depth from MP. Instead, Nawrot (2003) proposes that the model parameter *t* is served by an OKR eye movement signal. The current study investigates whether changes in viewing distance ($D_M$) produce a change in the perception of depth ($d_M$) from motion parallax ($\mu$) that co-varies with changes in the OKR signal.

While it is unclear what metric the visual system uses for the OKR signal, for the current study we use OKR gain to reflect the magnitude of the OKR signal. However, OKR gain is inversely proportional to the model parameter *t*. Consider, a fixed magnitude head movement (*t*) generates a smaller OKR eye movement as viewing distance increases; the use of OKR gain in the model preserves this relationship. When OKR gain is high (which occurs with near viewing distances and when the gain of TVOR is low), the resulting depth estimate is similar to the depth estimate generated by a smaller effective *t*. The predictions illustrated in Figure 1 stem from this hypothesis.

Figure 1 illustrates some possible results from a procedure in which BD is used to match the perception of depth from MP at various viewing distances. Assume motion parallax DE is fixed at 8 minarc at all viewing distances. The black line describes the result if observers require 8 minarc of BD to match the 8 minarc DE standard at each distance. The blue line describes the result if MP has less than perfect constancy and is perceived as compressed in depth. In this case, only 7 minarc of BD would be needed to match the depth portrayed by 8 minarc of DE. However, imagine that MP was matched by decreasing amounts of BD with increasing viewing distance. The red line in Figure 1A is one description of this hypothetical result. To illustrate this in regard to perceived depth, Figure 1B shows the disparity matches in Figure 1A transformed into perceived depth values using the distance-squared law.

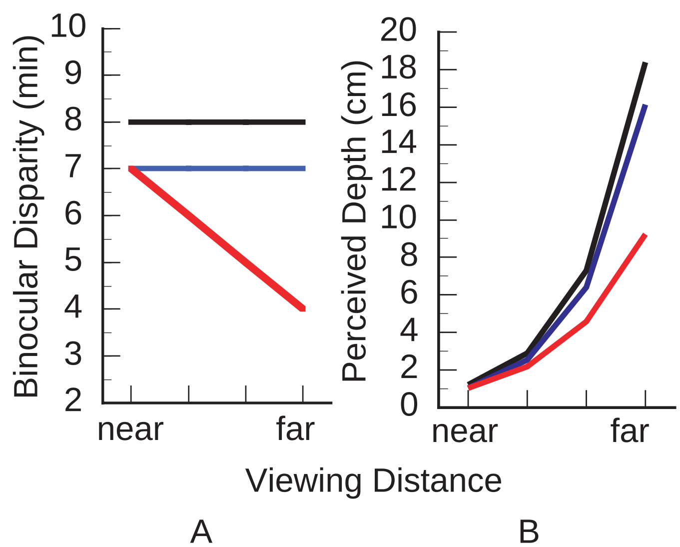


Figure 1. Possible results of a binocular disparity (BD) - motion parallax (MP) depth matching procedure. Lower matching values signify smaller magnitudes of depth perceived in the MP stimulus compared to the BD stimulus. (A) Possible matching results illustrated in BD values needed to match a MP standard. (B) The same possible matching results illustrated in terms of perceived depth. The black line shows perceived depth if MP and BD generated $d_S = d_M$ from $\delta = \mu$. The blue line shows MP generating a smaller depth percept than BD that is constant across viewing distances. The red line shows greater depth compression for MP compared to BD as viewing distance increases.

Incomplete depth constancy is commonly observed with MP; behavior like this is represented by the red lines in Figure 1A and 1B

Finally, what results are predicted if an OKR eye movement signal provides the necessary extra-retinal information required for recovery of unambiguous depth order in MP displays? Because OKR magnitude changes inversely with TVOR magnitude, which changes with viewing distance, OKR magnitude decreases with increasing viewing distance. If there is a connection between OKR and MP, depth scaling in a MP display should mirror changes in OKR gain (red lines). Considered with respect to Equation 2, the red line in Figure 1 also describes an increase in *t* (a decrease in OKR) with viewing distance.

# Methods

To index or measure the magnitude of perceived depth in a MP stimulus, MP was compared to BD in a two-interval, forced-choice (2IFC) depth magnitude comparison task. The first interval contained the MP stimulus with a fixed 8 minarc DE. The second interval contained the BD stimulus in which BD varied in a method of constant stimuli between 2 minarc and 14 minarc. The observer's task was to indicate which interval generated greater perceived depth. The amount of BD needed to match the fixed MP stimulus provides an index of the perceived depth in the MP stimulus.

To determine how this changed with viewing distance, observers performed the comparison at each of four different viewing distances. This change in perceived depth from MP could then be compared to the change in OKR gain over the same four viewing distances.

## Stimuli

The visual stimuli were computer-generated random-dot displays depicting a surface with a corrugated sinusoidal depth profile (Figure 2). The spatial frequency of the depth sinusoid was 0.4 c/d, the peak sensitivity found by Rogers and Graham (1982). Using this stimulus, identical sinusoidal depth information can be generated by both BD and MP (Rogers & Graham, 1982). The two matching BD and MP stimuli were randomly presented with one of two opposite depth profiles: the first cycle immediately above the fixation point could be either a peak or a valley. The BD and MP stimuli were always 180 degrees out of phase with each other so that observers made comparisons based on the stimulus depth rather than on the location of a particular peak or valley, or a local feature within a peak or valley.

The BD stimuli were created by assigning dots either crossed or uncrossed disparity, with the magnitude and sign of the disparity determined by a vertically oriented sinusoid function. Two versions of the stimulus, one for each eye, were prepared and were presented to the observer using a frame-sequential technique to create retinal disparity. To observers viewing the BD stimulus through the stereo apparatus, the dots appeared stationary and falling upon a smooth surface with a sinusoidal depth profile.

The MP stimuli were created by yoking the horizontal translation of dots to translation of the observer's head. Dots appearing nearer than fixation (a hill) moved in the direction opposite observer head movements while dots appearing farther than fixation (a valley) moved in the same direction as the observer's head movements. The amount of depth portrayed in the MP stimulus was controlled through the magnitude of dot movement for a given magnitude of observer head movement. For instance, dots appearing upon the peak of a hill had the greatest movement magnitude while dots falling along the slope had movements of lesser magnitude, again determined by a vertically oriented sinusoidal function. To observers viewing the MP stimulus monocularly, the dots appeared stationary and falling upon a smooth surface undulating in depth.

Four different viewing distances, differing in steps of 0.20 log units, were used: 57, 90, 143, and 227 cm. The random dot stimuli were designed so that stimulus parameters were as similar as possible at the four viewing distances. The size of the stimulus window remained constant on the monitor, therefore subtending a smaller area with increasing distance. Stimulus information presented within this window was changed over viewing distances so that the retinal stimulus remained constant (e.g., dots changed size on the monitor face so each subtended 2.0 minarc at all viewing distances). Table 1 gives values of several key stimulus parameters. In all cases white dots were drawn on a black monitor face. A small

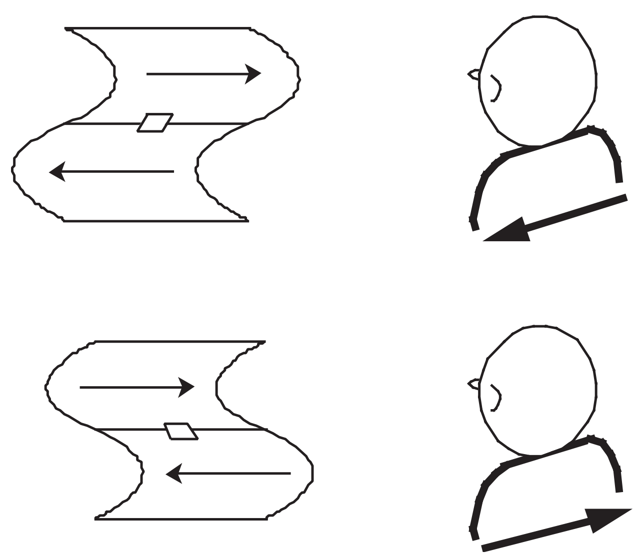

Figure 2. The sinusoidal depth profile of the stimuli and the relationship between observer translation and stimulus movement are shown.

Table 1. Stimulus Parameters for Each of the Four Viewing Distances.

| Viewing Distance | cm | 57 | 90 | 143 | 227 |
|---|---|---|---|---|---|
| Dot Size. | Minarc (pix) | 2.0 (1) | 2.5 (2) | 2.4 (3) | 2.0 (4) |
| # Dots | | 5000 | 3750 | 2500 | 1250 |
| # cycles | (0.4c/ deg) | 5.3 | 3.4 | 2 | 1.4 |
| Peak DE | Minarc (pix) | 8.0 (4) | 7.6 (6) | 8.0 (10) | 8.2 (16) |
| BD range | minarc | 2.0 – 14.0 | 2.5 – 14.0 | 1.6 – 14.4 | 2.0 – 14.3 |
| # stim. intervals | | 7 | 10 | 9 | 7 |

fixation square was drawn at the center of the stimulus. The central horizontal band of the stimulus, including the fixation square, always portrayed zero BD, or zero DE in the case of motion parallax.

To determine how OKR gain changed with viewing distance, eye movement and interaural head movements were measured in both light and dark conditions. Eye movement gain in light conditions (light gain) is a product of both the translational vestibular ocular response (TVOR) and of a visually driven optokinetic response (OKR), which together maintain perfect fixation on the target (gain = 1) during the observer's head movement. Eye movement gain in completely dark conditions (dark gain) is solely the product of TVOR as there are no visible contours to drive the visual OKR. That is, when an observer makes lateral head movements in complete darkness, the vestibular system still generates compensatory eye movements, in this case the TVOR, even though there is nothing visible to the eyes. These "dark" eye movements are smaller than would be required to maintain fixation if something were visible to the observer (gain < 1). Light gain (TVOR + OKR) was measured with the fixation point visible. Dark gain (TVOR) was measured in complete darkness with the fixation point extinguished as the observer initiated the head movement.

## Apparatus

The experimental apparatus was interfaced with the display-generating computer through a 12-bit analog-to-digital converter (ADC) with digital I/O capabilities (National Instruments; Austin, TX). All analog samplings and digital control signals were synchronized to the vertical refresh interrupt of the computer monitor.

A head movement apparatus was used to measure movement parallel to the interaural axis and restrict other translations and rotations of the observer's head. High viscosity silicone dental putty (Exaflex, GC America; Chicago, IL) was used to make dental impression over a stainless steel bite bar that was attached to a passive slide that translated laterally on linear bearings. Lateral translation of the slide required an average force of less than 1 N. A linear potentiometer (ETI Systems; Carlsbad, CA) connected to the head movement slide signaled head position to the nearest 0.1 mm along the entire 20 cm slide movement with excellent linearity ($r^2$ = 0.999). The calibration of this device remained very stable as it was checked periodically throughout the experiment. Because the device prevented tilting or rolling of the head, observers typically made head movements only within the central 12 cm of the device's travel.

Binocular disparity stimuli were presented using in a frame-sequential technique with ferro-electric LCD shutter glasses (Displaytech; Longmont, CO) generating interocular separation. These shutters have a 70 µsec transition and a 1000:1 contrast ratio between on and off states.

Eye position was monitored with a head-mounted infra-red limbus tracking system (Skalar; Delft, Netherlands). All eye movement recordings were made of the observer's right eye while the left eye was occluded.

## Procedure

### *Psychophysical depth matching*

Observers were seated in a darkened room with dim overhead lighting. Observers wore the shutter glasses and firmly clasped their teeth on the bite bar. In a two-interval forced-choice (2IFC) procedure, subjects were asked to report which interval contained the stimulus depicting greater depth. Observers initiated each trial with a key press. The various stimulus variables used at each of the four viewing distances are given in Table 1.

The first interval contained the MP stimulus with a fixed 8 minarc DE. The shutter glasses occluded the left eye's view of the monitor and allowed only the right eye to see the display. In this interval the stimulus appeared flat and static until the observer made a head translation parallel to the interaural axis creating a concomitant change to the MP display on the monitor. Observers were instructed to keep their eyes fixed on a small square at the center of the stimulus as they made head movements at a frequency between 0.5 and 1.0 hz. Following a short period of unrestricted viewing of this stimulus, the observer used a key press to transition into the second interval.

The second interval contained the BD stimulus that varied between trials in a method of constant stimuli between 2 minarc and 14 minarc. The shutter glasses showed alternate monitor refresh frames to either eye, creating stereoscopic depth. Observers maintained their bite on the bite bar and were instructed to keep their heads still and maintain fixation on the small square at the center of the stimulus. The observer then used a key to indicate which interval depicted the greater magnitude of depth.

Five observers (author and 4 naive participants) participated. Each observer completed four blocks of 44 trials. Each starting at 57 cm, all data for all observers at a particular viewing distance were collected before the computer monitor was moved to the next farthest viewing distance.

### *Eye movement gain*

To determine how OKR eye movement gain changes with viewing distance, both eye movements and interaural head movements were measured for observers at each of the four viewing distances. Observers were seated in a darkened room with the only illumination coming from the computerized display in front of them. A bite bar was used to restrict observer head movements. The bite bar also assured that the observers' head was rigidly attached to the translation apparatus, thereby making measurement of head translation possible. Eye movements were recorded from the right eye while an eye patch occluded the left eye. Following a brief calibration routine, observers fixated a small spot on the monitor while making translational head movements parallel to the interaural axis. In these "light gain" trials the fixation spot remained visible throughout the trial. Observers were instructed to make smooth lateral head movements while maintaining fixation. The head movement frequency was between 0.5 and 1 hz.

Eye and head movements were recorded for 6.5 seconds and typically included about three cycles of observer head movement. Immediately following each "light gain" trial with the fixation spot visible, the observer repeated the procedure in a "dark gain" trial. In these dark trials observers were instructed to maintain fixation on the imagined or remembered position of the spot as the monitor was extinguished and occluded the moment the observer began the first head movement. The room was completely and immeasurably dark during these head and eye movements. Observers made between five and eight recordings at each of the four viewing distances.

# Results

## Psychophysical Matching

The results were tabulated as the percentage of trials in which the BD stimulus was judged to have greater depth. Individual observers performed similarly for each viewing distance so the matching data were pooled for the analysis. For each viewing distance a psychometric function was fit to the cumulative data using an error function (erf) generating the best approximation to the cumulative normal (Figure 3).

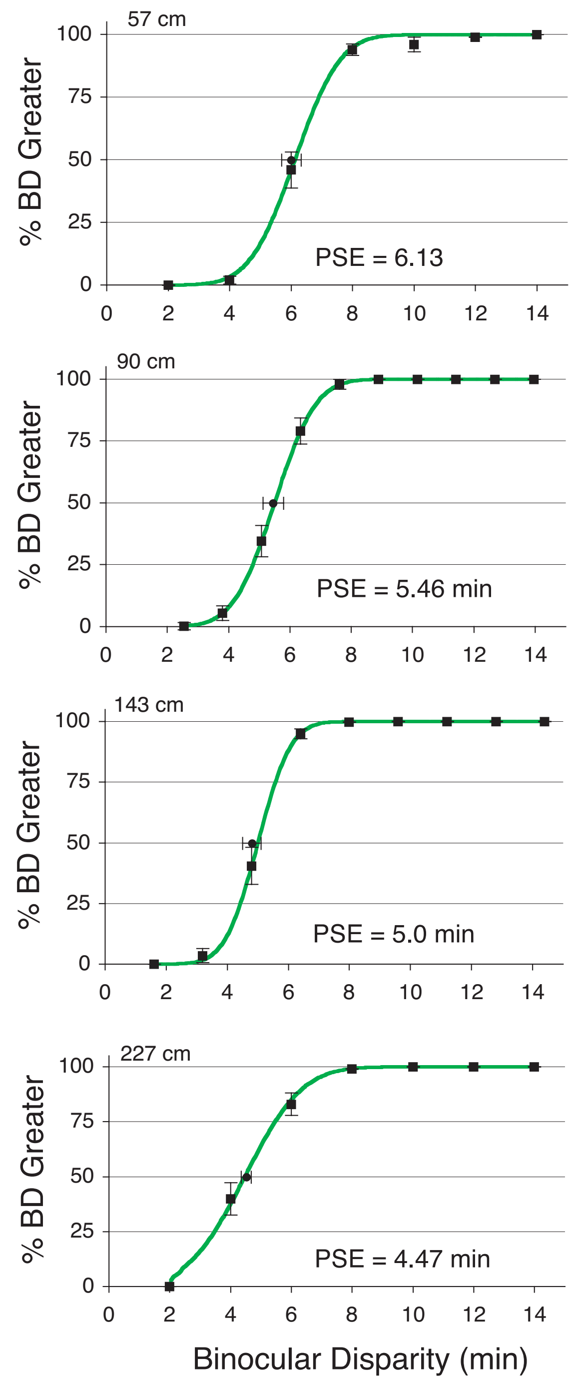


Figure 3. Psychometric functions and calculated points of subjective equality (PSE) at each of the four viewing distances. The horizontal axis shows the BD and the vertical axis gives the percentage of trials that the BD stimulus was judged to have greater depth. The filled squares show the average performance (+/- 1 SE) and the smooth line shows the best fitting error function (erf) used to determine the PSE values. The filled circles lying on the 50% line show the average PSE (+/- 1 SE) from individual observers.

The point of subjective equality (PSE) was determined from where these functions cross the 50% point. For increasing viewing distances, the psychometric functions and PSEs shift to lower values. This means that with increasing viewing distances, a smaller amount of BD is required to match the 8 minarc DE motion parallax standard. This result is consistent with the Ono et al., (1986) observation that depth constancy from MP begins to fail with increasing viewing distance in laboratory conditions employing lateral head movements.

## Eye Movement Gain Analysis

Figure 4 shows a typical raw eye and head movement recording in dark conditions at 57 cm with the imagined fixation point. The top tracing shows eye position and the lower tracing shows head position. It has been shown that TVOR is more robust at higher head movement frequencies (Paige et al., 1998; Telford et al., 1997), and the smooth TVOR responses show that the observer head movements were within the TVOR range. In contrast, the low frequency (0.5 hz) translations made by Paige et al's (1998) subjects were characterized by numerous saccadic eye movements when head movements were below the frequency range of the TVOR system.

To calibrate each trial, a line was fit to the calibration points and ADC eye position values. Trials for which the calibration was lower than $r = 0.97$ were excluded from the analysis, (about one quarter of the trials collected).

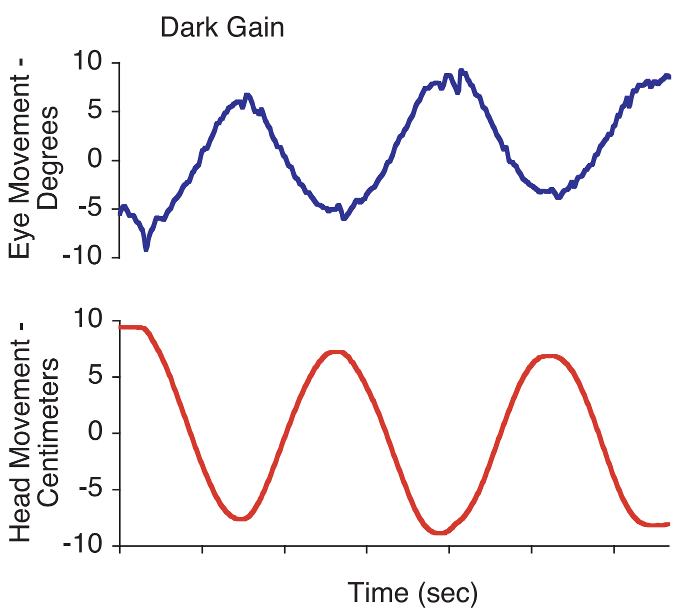


Figure 4. Eye movement (blue) and head movement (red) tracings from a dark gain trial. Each tick on the horizontal axis represents one second. Even in complete darkness, as the observer's head moved in one direction, TVOR eye movements were generated in the opposite direction. In the example shown, dark gain = 0.801.

Using this line, the *actual* eye movement recording was converted to units of degrees left and right of center. Using the head movement recording, the *expected* eye movements were determined in degrees left and right of center. Eye movement gain was determined by comparing the actual and expected eye movements for the central 7 to 10 degrees of translation to the left or right, excluding more extreme sections when both eye and head were slowing, reversing, and then accelerating. A regression was used to determine the relationship between actual and expected eye movements in this central section of each recording. Because the recording rate was fixed, the number of points included in the analysis depended on how fast the observer's head moved. The slope of the regression gave the gain of the eye movement for the accompanying head movement. The average gain for each trial was determined from four translations, two to the left, and two to the right.

Table 2 gives the average calibration, average gains, and the proportional change in OKR gain (*pOKRG*) with viewing distance. Optokinetic response gain was calculated by subtracting dark gain (TVOR alone) from light gain (TVOR + OKR). As expected, eye movement gain was very close to 1.0 in light conditions at all viewing distances. In dark conditions the eye movement gain was less than 1.0, representing under-compensation, but these dark gain values increased with larger viewing distances. Although the TVOR gain values are lower than those found by Paige and Tomko (1991), these values are within the range reported by Schwarz and Miles (1991). As will be discussed below, the frequency and amplitude of the head movement most likely plays a role both in eye movements (Telford et al., 1997; Paige et al., 1998) and in the perception of depth from motion parallax.

Compared to TVOR, the computed OKR component of the eye movement decreases with increased viewing distance. This means that as viewing distance increases, TVOR provides a larger portion of the compensatory eye movement and the OKR provides a smaller portion of the eye movement. The last column in Table 2, pOKRG, shows the decrease in OKR as viewing distance increases as a proportion of the value at 57 cm. At 90 cm the OKR component is only 90% of the OKR at 57 cm and this OKR component decreases to 77% and 66% at viewing distances of 143 cm and 227 cm respectively.

Comparison of the change in OKR gain and in perceived depth from MP is shown as a function of viewing distance in Figure 5A. The green line was determined from the PSE's in the psychophysical matching procedure above. It shows that depth from MP was matched by smaller amounts of binocular disparity as viewing distance increased. The red line shows the predicted change in matching BD if perceived depth from MP changed with the change in OKR gain at these viewing distances. The changes in OKR gain with viewing

Table 2. Calibration and Eye Movement Gain Values for Each of the Four Viewing Distances

| Viewing Distance | | Calibration $r^2$ | LIGHT GAIN | DARK GAIN | OKR Gain | pOKRG |
|---|---|---|---|---|---|---|
| 57 | AVE | 0.994 | 1.033 | 0.775 | 0.257 | |
| | St Err | 0.002 | 0.022 | 0.036 | 0.032 | |
| 90 | AVE | 0.986 | 1.017 | 0.785 | 0.232 | 0.903 |
| | St Err | 0.002 | 0.037 | 0.034 | 0.030 | |
| 143 | AVE | 0.988 | 0.993 | 0.795 | 0.198 | 0.770 |
| | St Err | 0.003 | 0.032 | 0.051 | 0.038 | |
| 227 | AVE | 0.995 | 0.970 | 0.801 | 0.169 | 0.658 |
| | St Err | 0.001 | 0.021 | 0.045 | 0.039 | |

distance are shown the last column of Table 2. For instance, the OKR gain at 90 cm viewing distance is 90.3% of the OKR gain at 57 cm. Therefore the second point on the red line in Figure 5 is 90.3% of the value at 57 cm. The starting point for this line is the psychophysical matching point for 57 cm because it is the change over viewing distance that is of central importance, not the specific value at 57 cm. For comparison, the black line depicts the line if 8 minarc DE of MP match 8 minarc of BD at each of the viewing distances. This is the same hypothetical line shown in Figure 1A.

Similar to Figure 1B, Figure 5B shows the disparity values transformed into perceived depth values. In this case, the change in perceived depth from MP predicted by the change in OKR gain is very similar to the change in perceived depth measured with the matching procedure.

Revisiting the distance-squared law mentioned in the

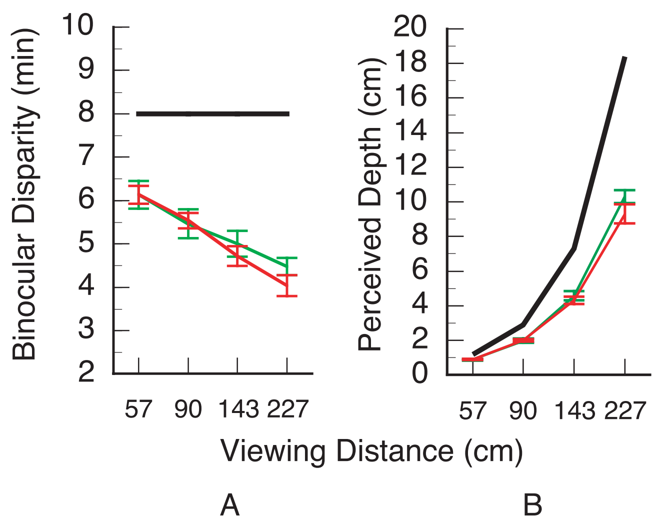


Figure 5. A) The BD-MP psychophysical matching data are shown with the green line. Each point is the PSE (+/- 1SD) derived from the error functions shown in Figure 3. Changes in BD predicted by changes in OKR gain (equation 2) (+/- 1 SE) are shown with the red line. B) The disparity values (and error) transformed into perceived depth values to better illustrate the failure of constancy with motion parallax.

introduction, the green line in Figure 5A is the result of the psychophysical measurement of $\delta$ (binocular disparity) matching a standard $\mu$ (disparity equivalence) at each viewing distance. The green line in Figure 5B gives the corresponding $d_M$ values. The red line in Figure 5A gives the expected $\delta$ value if $\delta$ measured at 57 cm changed with increased viewing distance as a function of the change in OKR gain (pOKRG) at these viewing distances as shown in Equation 4:

$$\delta_{90} = \delta_{57} * pOKRG_{90} \qquad (4)$$

Likewise, the red line in Figure 5B plots the corresponding $d_M$ values (Equation 3).

$$d_M = D_M^{2} * \mu * pOKRG / t \qquad (5)$$

The function shown in Equation 5 demonstrates that changes in $\mu$ and $d_M$ parallel the changes in OKR gain. This suggests a possible general form of the distance-square law for motion parallax.

This general form of the distance-square law for motion parallax relying on OKR gain, instead of head translation ($t$) is shown in Equation 6. While the specific metric of the OKR eye movement signal remains to be determined, we do know OKR gain and we know it maintains an inverse relationship with head movement magnitude. As OKR gain decreases, a larger head movement ($t$) is required to generate the same magnitude of OKR eye movement. An estimate of the total compensatory eye movement (assuming gain = 1) is generated with the function, $\theta = \arctan(t / D_M)$. However, since the visual system relies on the OKR component of the eye movement, not the total eye movement, and OKR gain is << 1, the estimate of the OKR eye movement needed in the distance-square law is given by $\theta / OKRGain$.

$$d_M = D_M^{2} * \mu \,/\, (\theta / OKRGain) \qquad (6)$$

As shown with the blue line in Figure 6, this function generates a reasonable approximation of the MP-BD matching procedure data. An even better approximation of the psychophysical data would be generated by higher OKR gain values at nearer viewing distances (57 cm to 143 cm) and lower OKR gain values at the 227 cm viewing distance.

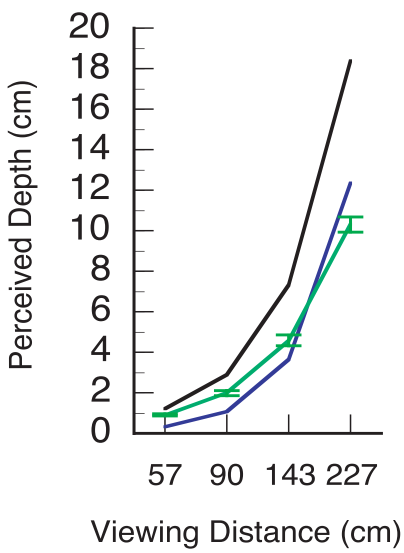


Figure 6. The blue line shows the predicted perceived depth values using Equation 6. These predicted values are a reasonable approximation of the perceived depth values calculated from the MP-BD psychophysical matching data (green line from Figure 5B).

The shortcoming of this approach is that the visual system does not monitor OKR gain, but instead uses some type of direct OKR eye movement signal. When the specific metric of the OKR eye movement signal used by the visual system is further resolved any reference to head translation and OKRGain (which relies on knowing head movement) should be replaced in the model.

# Discussion

These results suggest an answer to Ono et al's., (1986) original question: "Why does the effectiveness of (motion) parallax (created with head translations) decrease with viewing distance?" The answer appears to be that the OKR eye movements have a role in the perception of depth from MP (Nawrot, 2003) and these OKR eye movements vary inversely with viewing distance.

For MP created with quick lateral head translations and near viewing distances, a sizeable OKR eye movement is required to help the TVOR, which has a gain less than 1, to maintain fixation. The main result of the current experiment is the demonstration that changes in the OKR paralleled changes in the perceived depth from MP. Based on this result is it reasonable to expect that the perception of depth from MP generated with lateral head movements becomes even less effective at viewing distances larger than those used in the current experiment. At even larger viewing distances, OKR magnitude decreases, until TVOR gain = 1, and no OKR is required. At yet larger viewing distances the sign of the OKR must reverse as TVOR gain > 1, in order to suppress the over-compensation by the TVOR. In these cases of large viewing distances and lateral head translations, the OKR eye movement component is probably ineffective or even misleading for the perception of depth from MP. This might explain why most laboratory studies of MP have used viewing distances less than a meter.

However, it is important to consider that this does not mean that depth from MP is restricted to near viewing distances. Indeed, it is well known that MP can function over very large viewing distances when an observer is undergoing sustained translation as in a vehicle (Gibson, 1950). In this case the vestibular system is not activated, and no TVOR is generated. Instead, OKR (or the pursuit system) alone serves to compensate for observer translation and maintain fixation on a particular point in space. The same relationships between the direction of eye movement, the direction of object movement upon the retina, and the perceived relative depth are maintained under these viewing conditions as well. For MP under passive translation and large viewing distances, the OKR eye movement serves the exact function that it does in conditions of near viewing and lateral head movements. Perhaps it is even more effective as it does not have to work around the TVOR eye movements.

Dynamics of the TVOR and its interaction with the visually driven OKR suggests a mechanism underlying the dependence of MP thresholds on head movement velocity (Ujike & Ono, 2001). The TVOR has high pass characteristics meaning that the otolith-ocular system generates compensatory horizontal eye movements best in high frequency (1-4hz), high g-force head translations (Telford et al., 1997; Paige et al., 1998). At lower frequencies the otolith-ocular system may tend to generate torsional eye movement responses as if responding to tilt. However, as illustrated in the study above, large TVOR gain means small OKR responses and a deleterious effect for the perception of depth from MP. In an innovative study, Ujike and Ono (2001) found that below a head movement velocity of 13 deg/s, MP thresholds were limited by actual motion-perception thresholds. However, at larger head velocities MP thresholds increased as a function of head velocity. Similar to the results of the current experiment, Ujike and Ono found poorer perception of depth from MP in stimulus conditions where OKR eye movements decreased in magnitude. An even more interesting possibility is that the transition point between the two types of MP thresholds found by Ujike and Ono may correspond to the transition point between the low frequency (tilt) and the high frequency (TVOR) aspects of the otolith-ocular response system. The higher head velocity of Ujike and Ono might fall within the high pass range of the TVOR system and therefore cause a decrease in OKR, while their lower head velocity did not.

While it is known that eye movements and the visual-vestibular interactions that produce them contribute to many motion perception phenomena (Post & Leibowitz, 1985), the role of these mechanisms in the perception of depth from motion parallax is only beginning to be understood.

## Conclusions

This study provides further support for the theory that OKR eye movements play a role in the perception of depth from motion parallax. Earlier results show that that the direction of OKR eye movement provides information needed for unambiguous depth sign from motion parallax (Nawrot, 2003). The current study shows that OKR magnitude and perceived depth from motion parallax do, in fact, co-vary. A transformation of the distance-squared law that takes into account OKR eye movement generates a reasonable approximation of the perceived depth from motion parallax.

## Acknowledgments

This research was supported by National Institutes of Health Grant EY-12541. A portion of this work was presented at the 2000 annual meeting of the Association for Research in Vision and Ophthalmology (Nawrot, 2000). The author appreciates the helpful comments offered by Randolph Blake, Martin Banks, and Elizabeth Nawrot. Commercial relationships: none.

## References

Bradshaw, M.F., Parton, A.D., & Eagle R.A. (1998.) Interaction of binocular disparity and motion parallax in determining perceived depth and perceived size. *Perception*, *27*, 1317-1331. [PubMed]

Bradshaw, M.F., Parton, A.D., & Glennerster, A. (2000). Task dependent use of binocular disparity and motion parallax information. *Vision Research*, *40*, 3725-3734. [PubMed]

Braunstein, M. L. & Tittle, J. S. (1988). The observer-relative velocity field as the basis for effective motion parallax. *Journal of Experimental Psychology: Human Perception and Performance*, *14*, 582-590. [PubMed]

Bronstein, A. M. & Gresty, M. A. (1988). Short latency compensatory eye movement responses to transient linear head acceleration: a specific function of the otolith-ocular reflex. *Experimental Brain Research*, *71*, 406-410. [PubMed]

Cormack, R, & Fox, R., (1985). The computation of retinal disparity. *Perception and Psychophysics*, *37*, 176-178. [PubMed]

Gibson, J.J. (1950). *The perception of the visual world.* Boston: Houghton Mifflin Co.

Howard, I. P. & Rogers, B. J. (2002). *Seeing in Depth*, Volume 2, Depth Perception. Toronto: I Porteous.

Miles, F. A. & Busettini, C. (1992). Ocular compensation for self-motion: Visual mechanisms. *Annual Review of the New York Academy of Science*, *656*, 220-232. [PubMed]

Nawrot, M. (2003). Role of slow eye movements in depth from motion parallax. *Vision Research*, *43*, 1553-1562. [PubMed]

Nawrot, M. (2000). Viewing distance, eye movements, and the perception of relative depth from motion parallax. *Investigative Ophthalmology and Visual Science*, *41*( 4), S45

Oas, J.G., Baloh, R.W. Demer, J.L., & Honrubia, V.L. (1992). The effect of target distance and stimulus frequency on horizontal eye movements induced by linear acceleration on a parallel swing. *Annual Review of the New York Academy of Science*, *656*, 874-876. [PubMed]

Ono, M.E., Rivest, J., & Ono, H. (1986). Depth perception as a function of motion parallax and absolute-distance information. *Journal of Experimental Psychology: Human Perception and Performance*, *12*, 331-337. [PubMed]

Ono, H. & Steinbach, M. J. (1990). Monocular stereopsis with and without head movement. *Perception & Psychophysics*, *48*, 179-187. [PubMed]

Ono, H. & Ujike, H. (1994). Apparent depth with motion aftereffect and head movement. *Perception*, *23*, 1241-1248. [PubMed]

Paige, G. D., Telford, L., Seidmen, S. H. & Barnes, G. R. (1998). Human vestibuloocular reflex and its interactions with vision and fixation distance during linear and angular head movement. *Journal of Neurophysiology*, *80*, 2391-2404. [PubMed] [Article]

Paige, G. D. & Tomko, D. L. (1991). Eye movement responses to linear head motion in the squirrel monkey. II. Visual-vestibular interactions and kinematic considerations. *Journal of Neurophysiology*, *65*, 1183-1196. [PubMed]

Post, R. B. & Leibowitz, H. W. (1985). A revised analysis of the role of efference in motion perception. *Perception*, *14*, 631-643. [PubMed]

Rivest, J., Ono, H., & Saida, S. (1989). The roles of convergence and apparent distance in depth constancy with motion parallax. *Perception & Psychophysics*, *46*, 401-408. [PubMed]

Rogers, B. J. & Collett, T.S. (1989). Appearance of surfaces specified by motion parallax and binocular disparity. *Quarterly Journal of Experimental Psychology*, *41*, 697-717. [PubMed]

Rogers, B. J. & Graham, M. E. (1979). Motion parallax as an independent cue for depth perception. *Perception*, *8*, 125-134. [PubMed]

Rogers, B. & Graham, M. (1982). Similarities between motion parallax and stereopsis in human depth perception. *Vision Research*, *22*, 261-270. [PubMed]

Rogers, S. & Rogers, B.J. (1992). Visual and nonvisual information disambiguate surfaces specified by motion parallax. *Perception & Psychophysics*, *52*, 446-452. [PubMed]

Schwarz, U., Busettini, C. & Miles, F. A. (1989). Ocular responses to linear motion are inversely proportional to viewing distance. *Science, 245*, 1394-1396. [PubMed]

Schwarz, U. & Miles, F. A. (1991). Ocular responses to translation and their dependence on viewing distance. I. Motion of the observer. *Journal of Neurophysiology, 66*, 851-864. [PubMed]

Steinbach, M. J., Ono, H. & Wolf, M. E. (1991). Motion parallax judgements of depth as a function of the direction and type of head movement. *Canadian Journal of Psychology*, *45*, 92-98. [PubMed]

Telford, L., Seidman, S.H., & Paige, G.D. (1997). Dynamics of squirrel monkey linear vestibuloocular reflex and interactions with fixation distance. *Journal of Neurophysiology*, *78*, 1775-1790. [PubMed] [Article]

Ujike, H. & Ono, H. (2001). Depth thresholds of motion parallax as a function of head movement velocity. *Vision Research*, *41*, 2835-2843. [PubMed]