Induced motion in depth and the effects of vergence eye movements

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Induced motion is the false impression that physically stationary objects move when in the presence of other objects that really move. In this study, we investigated this motion illusion in the depth dimension. We raised three related questions, as follows: (1) What cues in the stimulus are responsible for this motion illusion in depth? (2) Is the size of this illusion affected by vergence eye movements? And (3) are the effects of eye movements different for motion in depth and for motion in the frontoparallel plane? To answer these questions, we measured the point of subjective stationarity. Observers viewed an inducer target that oscillated in depth and a test target that was located directly above it. The test target moved in phase or out of phase with the inducer, but with a smaller amplitude. Observers had to indicate whether the test target and the inducer target moved in phase or out of phase with one another. They were asked to keep their eyes either on the test target or on the inducer. For motion in depth, created by binocular disparity and retinal size change or by binocular disparity alone, we found that when the eyes followed the inducer, subjective stationarity occurred at approximately 40–45% of the inducer's amplitude. When the eyes were kept fixated on the test target, the bias decreased tenfold to around 4%. When size change was the only cue to motion in depth, there was no illusory motion. When the eyes were kept on an inducer moving in the frontoparallel plane, induced motion was of the same order as for induced motion in depth, namely, approximately 44%. When the induced motion was in the frontoparallel plane, we found that perceived stationarity occurred at approximately 23% of inducer's amplitude when the eyes were kept on the test target.

Keywords: motion in depth, induced motion, vergence, eye movements


Introduction

Induced motion is the false impression that a physically stationary stimulus moves relative to the head in the presence of other stimuli that really move. For example, if a large moving pattern is shown to an observer and a small stationary target is then displayed in front of or behind the pattern, the stationary target will appear to move in a direction opposite to the motion of the large pattern. This illusory motion is known as the Duncker illusion (e.g., Duncker, 1929/1938; for a review on induced motion, see, for example, Mack, 1986). This definition can be expanded to include situations where moving stimuli are seen to be faster in the presence of other stimuli that move in the opposite direction or slower when in the presence of stimuli that move in the same direction. The conventional explanation for this illusion is that motion of the stationary target is perceived because the relative motion between the target and the large pattern is the effective cue. The absolute motion of the image of the target over the retina, or lack thereof, is only of minor importance for perceived motion. Induced motion has been studied extensively in the frontoparallel plane. Induced motion in the depth dimension on the other hand has received far less attention. In the present paper, we address three fundamental questions about induced motion in depth. First, we wanted to find out which stimulus characteristics can induce motion in depth in a stationary target. Second, we raised the question of whether induced motion in depth depends on the eye movements that are made when viewing the scene. And, third, we wanted to know if the effect of eye movements on motion perception was different for motion in depth and for motion in the frontoparallel plane.

Earlier findings on motion perception and its interaction with eye movements in the frontoparallel plane cannot be generalized to motion in depth (Nefs & Harris, 2007). An important reason is that there are several motion-in-depth cues that are not available for motion in the frontoparallel plane. First, there is size change. The angular size of an object on the retina increases when an object comes closer because of perspective projection. The second cue is the total luminance change that is associated with size change. The light intensity per image point remains the same; objects do not increase in intensity as they approach. The total amount of light coming from the object that enters the eye increases when the object comes closer. This
increase is however proportional to the increase in image size on the retina. The third cue to a change in depth is a change in binocular disparity. All three cues give a compelling sense of motion in depth.

Ittelson (1951) was the first to discuss induced motion in the depth dimension. He showed two binocular targets, one of which was moving in depth, to his observers. The second target remained stationary. Based on qualitative descriptions, Ittelson reported “at best a very slight induced movement effect” in the stationary target. Farné (1972, 1977) conducted a series of studies on induced motion in the depth dimension. He showed that stationary stimuli are perceived as moving in depth when surrounded by stimuli that physically move in depth. The observers viewed the stimuli monocularly in all his experiments. Therefore, the only cues to motion in depth were the apparent size change and the change in the total amount of light impinging from the target on the retina. Gogel and Griffin (1982) investigated induced motion in the frontoparallel plane and induced motion in depth for binocular viewing conditions. They used a vertically moving test target and two horizontally moving inducer targets for induced motion in the frontoparallel plane. In the case of motion in depth, the inducers moved in the depth dimension. Changing the binocular disparity of the inducers created the perception of motion in depth. The observer had to indicate the perceived slant of the path of the test target. The perceived slant was taken as a measure of induced motion. Gogel and Griffin found a large amount of induced motion in the frontoparallel plane as well as in the depth dimension. Harris and German (2008) compared induced motion in the frontoparallel plane with induced motion in depth using binocular disparity as the depth cue. They found no difference in the amount of induction when retinal motion was of the same magnitude for frontoparallel motion and motion in depth. Likova and Tyler (2003) found stereomotion induction in dynamic autostereograms consisting of lines of discs. Because of the nature of autostereograms, these stimuli do not have the appropriate structure to induce lateral motion in each eye separately. Hence, they claimed that the induction they reported must be a truly binocular phenomenon operating on binocular disparities.

It has been shown that motion can be induced in stationary objects irrespective of whether the induced or the inducer targets are fixated (e.g., Gogel & Griffin, 1982). Gogel and Griffin (1982) included eye movements as an experimental factor in their design. Observers had to fixate on the test target or on one of the moving inducer targets. Substantial amounts of induced motion were found in both fixation conditions. There was no main effect of fixation condition, but there was a significant interaction of fixation condition with the frequency of oscillation of the inducer dots. Induced motion in depth was larger for low-frequency (0.16 Hz) as compared with high-frequency motion (0.33 Hz) when the test dot was tracked with the eyes, and induced motion was smaller for low-frequency as compared with high-frequency motion when the eyes followed the inducers. Likova and Tyler (2003) also did not find a difference in the amount of induced motion when the physically moving inducers were fixated and when the physically stationary targets were fixated.

In this paper, we report two related experiments. In Experiment 1, we investigated the effect of eye movements on induced motion in depth under three different conditions. In the first condition, all motion-in-depth cues were present. In the second condition, the stimulus only changed its size. We kept the binocular disparity constant. In the third condition, the targets did not change in size, but only their binocular disparity changed. In Experiment 2, we compared the effect of eye movements on induced motion in the frontoparallel plane with the effect of eye movements on induced motion in depth.

### Experiment 1

#### Method

##### Observers

Two female and three male observers with ages ranging between 20 and 38 years contributed data in the main experiment. Two more male observers in the same age range contributed data to the two control conditions. Observers H.N. and J.H. were the authors of this paper. Observers R.G., J.B., and V.D. were semi-naive coworkers. Observers S.A. and A.C. were naive to the purposes of the experiment. We prescreened all observers for visual acuity, color vision, and stereovision. All observers had normal or corrected-to-normal vision. They also reported not having had any ophthalmologic problems in the past. The Teaching and Research Ethics Committee of the School of Psychology at the University of St. Andrews approved all experiments reported in this paper.

##### Materials

We used a Dell workstation to present the stimuli on an Iiyama 22-in. Vision-Master-Pro monitor with a resolution of 1280 × 1024 pixels and a refresh rate of 100 Hz. To create binocular disparity, we presented anaglyph images of the stimuli. We used red and blue guns of the monitor for the right and the left eye, respectively. Observers wore a red filter in front of the right eye and a green filter in front of the left eye. We used a green filter rather than a blue filter because the infrared illumination of the eye tracker does not pass through a blue filter. A blue stimulus gave a better luminance separation between the two half images than a green stimulus. Luminance as seen through the filters was 0.17 cd/m² for each eye for the corresponding color and 0.01 cd/m² for the noncorresponding color.
The latter value was indistinguishable from the background luminance. The interocular distance used in all calculations was 6.25 cm.

Eye movements were recorded binocularly at 250 Hz with a video-based infrared eye tracker (SR-Research, EyeLink-II). Data were saved to disk for off-line analysis.

Procedure

The observer was seated in a dark room with the head placed on a chin rest at 1.0 m distance from the monitor. The tip of the nose was pressed gently against a small placeholder. The edges of the screen were not visible in the dark. We used a one-interval 2AFC paradigm with the method of constant stimuli to measure the psychometric function for the discrimination of the direction of motion in depth of a small target dot.

In each trial, two circular targets were shown: one at eye height, straight ahead at 1.0 m distance, and a second target also straight ahead at 1.0 m distance but 3.2 degrees (5.6 cm) above the first target. The targets were 22 arcmin in diameter at a 1-m distance. At the beginning of a trial, both targets appeared and were stationary for 500 ms. After that, the target at eye height, which we will call the inducer target, started to oscillate in depth with its starting position at the center of oscillation. This center of oscillation was in the plane of the computer monitor. The inducer target oscillated sinusoidally for 12 s with a frequency of 0.333 Hz and a peak-to-peak amplitude of 40 cm. The maximum absolute speed during the oscillation of the inducer was 41.89 cm/s, which corresponds to a maximum absolute speed of 1.6 deg/s change in binocular disparity and a maximum speed in the change in the diameter of the target of 5.0 arcmin/s. The mean absolute speed during the oscillation of the inducer was 26.67 cm/s, which corresponds to a 1.0 deg/s change in binocular disparity and a 3.0 arcmin/s change in the diameter of the inducer target. The upper target, the test target, was given a small amount of motion in depth, which could be either in phase or 180 degrees out of phase with the inducer target for the duration of the trial. At the end of the trial, both targets disappeared, and the observer was prompted to indicate with a button press on the computer keyboard whether the test (upper) target moved in phase or out of phase with the inducer (lower) target.

We used a 2 × 3 factorial design. The first factor, eye movement, had two levels: In the “eyes on inducer” condition, observers were instructed to follow the inducer target with their eyes, and in the “eyes on the test” condition, observers were instructed to keep their eyes on the test target. The second factor, cue type, had three levels. In the first level, “all cues,” the targets changed both in binocular disparity and in size when they moved in depth. In the second condition, “size only,” the targets only changed in size when the targets moved closer or further away according to the laws of linear perspective. For this condition, we kept the binocular disparity constant, congruent with a distance of 1 m (screen distance). In the third condition, “disparity only,” the targets changed only in binocular disparity when they moved in depth. We kept the size of the targets on the computer monitor constant, congruent with a distance of 1.0 m. All three cue-type conditions gave a convincing impression of motion in depth of the inducer target.

We used nine different test amplitudes for the test (upper) target with equilnear spacing. Two different ranges were applied, depending on experimental condition, because pilot results had shown that we could expect a considerable difference between different conditions; we used −35%, −26.25%, −17.5%, −8.75%, 0%, 8.75%, 17.5%, 26.25%, and 35% of the inducer’s peak-to-peak amplitude for the “eyes on test” condition and −5%, 3.75%, 12.5%, 21.25%, 30%, 38.75%, 47.5%, 56.25%, and 65% of the inducer’s peak-to-peak amplitude for the “eyes on inducer” condition in the “all cues” and the “disparity-only” conditions. For the “size-only” condition, we used test values of −35%, −26.25%, −17.5%, −8.75%, 0%, 8.75%, 17.5%, 26.25%, and 35% of the inducer’s amplitude for the “eyes on test” condition and −70%, −52.5%, −35%, −17.5%, 0%, 17.5%, 35%, 52.5%, and 70% of the inducer’s amplitude for the “eyes on inducer” condition.

The experiment was divided into 72 blocks of nine trials each. Each block of nine trials contained the complete set of nine test speeds for the condition that was measured in that set. The three cue-type conditions were each measured in 24 consecutive blocks. The order of the cue-type condition was randomized anew for each observer. The order of “eyes on test” and “eyes on inducer” was randomized over the experiment. The experiment was spread out over 12 sessions. Each session consisted of four blocks of nine trials. A block of nine trials took about 5 min. Prior to each block of nine trials, we performed a nine-point binocular eye calibration and verification procedure on the eye tracker. A typical session, including setting up and calibrating the eye tracker, took about three quarters of an hour. After a session of four blocks, observers took a break of at least a few hours. At the start of each block of nine trials, the observer was instructed to keep their eyes on the inducer (lower) target or on the test (upper) target.

We also tested two control conditions for this experiment. In the first control condition, we tested observers in the “all cues” condition, but with inducer and test amplitudes that were half the value of the amplitudes used in the main experiment. We measured this control condition to verify that the effects that we found were not due to the possibility that the disparities used in the main experiment were outside the range of quantitative stereopsis. We used the larger disparity in the main experiment to ensure a good separation in eye movement behavior between the two fixation conditions. Further, with smaller amplitudes in the main experiment, the “size-only” condition would have been very difficult to see.
In the second control condition, we measured induced motion, as described above, in the “size-only” condition for four observers but under monocular viewing conditions with the dominant eye instead of binocular viewing. The dominant eye was determined using the sighting test (e.g., Howard & Rogers, 2002).

Blocks of trials that turned out to have flawed eye movement recordings in the majority of trials due to, for example, substantial eyelid closure were repeated at the end of the experiment. No eye data were obtained for observer J.B. We were unable to obtain reliable data for this observer from the eye tracker because we had great difficulty getting a good lock on the pupil.

Results

Psychophysics

We fitted cumulative Gaussian functions to the psychophysical data, using the Levenberg–Marquardt method with the mean and the slope of the cumulative Gaussian function as free parameters. We define the bias as the test amplitude at which the observer says 50% of the time that the test target moves with the inducer and 50% of the time that it moves against the inducer; in other words, the point of subjective stationarity. We interpret the bias as the size of induced motion, that is, the amount of motion of the test target that is necessary to make the test target appear stationary in the presence of the inducer. Observers did not report seeing motion in depth in the test target near the point of subjective stationarity. The discrimination threshold is defined as the difference in stimulus intensity between the bias and the stimulus intensity, where the observer reports in 75% of the cases that the test moves in phase with the inducer. We calculated the estimated within-observer variances of biases and thresholds with Monte Carlo simulations (1000 throws) on the derived psychometric functions.

Results are shown in Figure 1. Rows A, B, and C show data for the “all cues,” the “size-only,” and the “disparity-only” conditions. On the left side of Figure 1, we show examples of fitted psychometric functions from observer H.N. The middle column shows the biases, and the right column shows the discrimination thresholds for all observers. The results for the “eyes on inducer” condition are shown in dark gray, and the results for the “eyes on test” condition are shown in a lighter shade of gray. The results labeled “ALL” were obtained by averaging over biases/thresholds over all five observers. Positive values for the bias indicate that the motion of the test target is in phase with the inducers.

We found that for the “all cues” condition, the mean bias was 3.5% (SD = 7.7%) for the “eyes on test” and 43.9% (SD = 9.9%) for the “eyes on inducer” condition. For the “size-only” condition, we found that the mean biases were −0.1% (SD = 3.0%) and −0.7% (SD = 11.0%) for “eyes on test” and “eyes on inducer,” respectively. For the “disparity-only” condition, we found that the mean biases were 4.0% (SD = 15.6%) and 46.0% (SD = 6.6%), respectively. The mean biases were not significantly different from zero, except when the eyes were on the inducer and the cue type was either “all cues” or “disparity only”, t(4) = 9.88, p < .001, and t(4) = 15.63, p < .001, respectively.

We performed a 2 × 3 (Eye movement × Cue type) repeated-measures analysis of variance (ANOVA) on the biases. There were significant main effects of both cue type and eye movement, F(2,8) = 32.43, p < .001, and F(1,4) = 56.64, p < .002, respectively. The interaction between eye movement and cue type was also significant, F(2,8) = 27.07, p < .001. We further analyzed the interaction with separate nine paired t tests. We accordingly adjusted the alpha criterion for multiple comparisons to .05/9 = .006. All p values are for two-tailed tests. In the “all cues” and the “disparity-only” conditions, the biases were significantly larger for the “eyes on inducer” as compared with the “eyes on test” condition, t(4) = 8.26, p < .001, and t(4) = 6.69, p < .003, respectively. The difference between the biases in the “eyes on test” and the “eyes on inducer” conditions was not significant for the “size-only” condition. We also found that the mean bias for the “size-only” condition was significantly lower than the mean bias for both “all cues” and “disparity only” in the “eyes on inducer” condition, t(4) = 12.08, p < .001, and t(4) = 16.91, p < .001, respectively. The mean bias for the “size-only” condition was not significantly different from the mean bias in the “all cues” and the “disparity-only” condition for “eyes on test.” None of the t tests revealed a significant difference between the biases in the “all cues” and the “disparity-only” conditions.

Next, we looked at the discrimination thresholds. Discrimination thresholds for the “eyes on test” were 4.6% (SD = 2.5%), 8.9% (SD = 6.9%), and 15.4% (SD = 10.3%) for the “all cues,” the “size-only,” and the “disparity-only” conditions, respectively. For the “eyes on inducer” condition, discrimination thresholds were 11.2% (SD = 5.3%), 47.4% (SD = 22.4%), and 14.2% (SD = 8.6%) for the “all cues,” the “size-only,” and the “disparity-only” conditions, respectively.

We performed a 2 × 3 (Eye movement × Cue type) repeated-measures ANOVA on the discrimination thresholds. There was a significant main effect of eye movement, F(1,4) = 12.56, p < .024, and of cue type, F(2,8) = 6.84, p < .019. The interaction between eye and cue type also proved to be significant, F(2,8) = 40.52, p < .001. We further analyzed the interaction with nine separate paired t tests comparing the “eyes on test” with the “eyes on inducer” conditions for the three cue types. Accordingly, we adjusted the alpha criterion for multiple comparisons to .05/9 = .006. None of the t tests were significant at this criterion. One t test approached significance closely. We found that the mean discrimination threshold in the “size-only” condition was almost significantly lower for the “eyes on test” condition as compared with the “eyes on inducer” condition, t(4) = 5.15, p < .007.
When using half the inducer amplitude in depth in the “all cues” conditions, we essentially found the same patterns as in the main experiment. Results are shown in Figure 2. The mean bias across observers was 1.9% (SD = 5.5%) when the eyes were kept on the test target and 40.2% (SD = 7.0%) when the eyes were kept on the inducer. The mean bias was significantly different from 0 when the eyes were kept on the inducer, $t(3) = 11.57$, $p < .001$, but not when the eyes were kept on the test target. A paired $t$ test indicated a significant difference between the two eye conditions, $t(3) = 8.20$, $p < .004$. The mean discrimination thresholds across observers were 4.5% (SD = 1.7%) when the eyes were kept on the test target and 19.2% (SD = 5.8%) when the eyes were kept on the inducer target. The difference in the mean discrimination threshold between the two eye movement conditions was significant at an alpha level of 5%, $t(3) = 3.93$, $p < .029$.

When the stimuli in the “size-only” condition were viewed under monocular viewing conditions, we also essentially found the same results as in the main experiment; namely, the mean biases across observers in either the “eyes on test” (−1.1%, SD = 3.3%) or “eyes on inducer” condition (−11.3%, SD = 20.4%) were not significantly different from 0, and they were not significantly different from each other. As in the main experiment, the mean discrimination threshold was higher when the eyes were kept on the inducer (45.5%, SD = 28.0%) than when the eyes were kept on the test target (9.1%, SD = 7.0%). The difference did however not reach significance this time. Results for all four observers are shown in Figure 3.

In summary, we found that for the “all cues” and the “disparity-only” cue, induced motion was on the order of 3.5–4.0% of the inducer amplitude when the eyes were looking at the test target. When the eyes followed the inducer, target-induced motions increased over tenfold to 43.9% and 46.0% of the inducer amplitude. There was no induced motion in depth when size was the only motion-in-depth cue. Looking at the discrimination thresholds, we
found that they were larger when the eyes were kept on
the inducer than when they were kept on the test target.
There was a significant interaction between eye movement
and cue condition. We found that the largest difference in
discrimination threshold between the two eye conditions
was in the “size-only” condition.

Eye movements

To test whether there is a difference in eye movements
over the different stimulus conditions and to ensure that
observers correctly performed the task, we measured eye
movements. A typical recording of a vergence eye
movement to the stimulus is shown in Figure 4. Vergence
is defined as the angle between the viewing directions of
the two eyes.

We performed a fast Fourier transform on the vergence
movements. We define the vergence response as the
Fourier component at 0.333 Hz (the temporal frequency
of the targets). Because the targets were simulated to
move sinusoidally in physical space, the movement of the
targets is slightly asymmetrical when expressed in angular
units (degrees). We evaluate the eye movements in
angular units. This causes a shift in the DC component
and some spillover in the harmonics of 0.333 Hz. The
largest spillover is in the first harmonic (0.666 Hz) and is
approximately 10% of the amplitude of 0.333 Hz. The
second harmonic (1.0 Hz) is approximately 10% of the
amplitude at the first harmonic; subsequent harmonics are
each likewise proportionally smaller. The energy con-
tained in the first harmonic has around the same range as
the noise in the vergence response when the eye is
stationary. Therefore, we considered it sufficient to look at
the fundamental frequency (0.333 Hz) only. The phase lag
is defined as the lag of the vergence response behind the
motion of the inducer target. A negative lag is a delay of

![Figure 4](image_url)

Figure 4. An example of a vergence eye trace from observer R.G.
The thick black sinusoidal curve shows the stimulus motion, and
the gray curve shows the vergence movements.
the vergence response relative to the inducer oscillation; a positive lag is an anticipation of the target motion.

We also calculated the vergence slip, that is, the difference between the stimulus motion and the eye movement. Vergence slip was calculated with Equation 1 for the 0.333-Hz component. In this equation, \( a \) and \( b \) are the amplitudes of the stimulus and eye movement, respectively, and \( \vartheta \) is the phase lag of the eye movement relative to the stimulus motion. On the right side of the equation, \( c \) indicates the amplitude of the vergence slip, and \( \varphi \) indicates the phase lag of the vergence slip relative to stimulus motion. Note that this analysis is equivalent to subtracting the raw eye movements from the stimulus motion and then looking at the 0.333-Hz Fourier component.

\[
a \sin(t) - b \sin(t + \vartheta) = c \sin(t + \varphi),
\]

where

\[
c = \sqrt{a^2 + b^2 - 2ab \cos(\vartheta)}
\]

\[
\varphi = \arctan \left( \frac{-b \sin(\vartheta)}{a - b \cos(\vartheta)} \right)
\]

All vergence responses and phase lags are summarized in Figure 5 for observer J.H. This observer is representative of all other observers. Mean vergence responses, phase lags, and vergence slips are shown for all observers in Table 1 for the “eyes on inducer” condition. The three rows in Figure 5 are for the three cue-type conditions. In the left column of Figure 5, we show the amplitude of the vergence response as a function of the test amplitude, and in the right column, we show the phase lag of the vergence response. The dark data points represent trials in which the eyes follow the inducer, and the light gray data points are the vergence responses when the eyes are kept fixated on the test target. We connected the mean amplitudes and mean phase lags per test amplitude with thick lines. The thin straight lines represent the motion of the inducer and the test targets. The vergence response increases when the absolute amplitude of the test target increases and when the eyes are on the test target and the motion-in-depth cue is “all cues” or “disparity only.” When changing the size of the target on screen was used to simulate motion in depth, the vergence response was not significantly dependent on the test amplitude. There is no systematic vergence response when change in size is the only cue to motion in depth. The amplitudes and phase lags in the “size-only” condition are indicative of the noise in the eye movements.

Next we looked at whether the vergence response, phase lags, and vergence slips were related to the observers’ responses. We calculated the mean vergence response, phase lags, and vergence slips for all trials in which the observer responded “in phase” and for trials where they responded “out of phase.” We did this for all test values that had a probability of responding “in phase” between .25 and .75. This ensures between three and nine trials in each response category. In Figure 6, we plotted the mean vergence responses, phase lags, and vergence slips for the trials in which the response was “in phase” against the trials in which the response was “out of phase.” The best-fitting lines as calculated by a least-squares type II regression through the data points are also shown in Figure 6.

In the “disparity-only” condition, the mean vergence response was higher for the “out-of-phase” answers as compared with the “in-phase” responses (0.50 vs. 0.47 degrees), \( t(12) = 2.43, p < .031 \). Also in the “disparity-only” condition, the mean vergence slip was lower for the “out-of-phase” responses as compared with the “in-phase” responses (0.29 vs. 0.33 degrees), \( t(12) = 2.32, p < .039 \). Other differences in the mean vergence response, phase lag, or vergence slip were not significant at an alpha level of .05.

We also tested the slopes of the best-fitting lines between the “in-phase” responses and the “out-of-phase” responses against the value 1. Best-fitting lines are shown in Figure 6. We found significantly different slopes for the vergence response in the “all cues” condition, \( t(8) = 4.81, p < .001 \), and in the “disparity-only” condition, \( t(11) = 2.50, p < .015 \). The slope of the best-fitting line was also significantly lower than 1 for the phase lags in the “disparity-only” condition. The slopes were significantly lower than 1 for the vergence slips for the “all cues” and the “disparity-only” conditions, \( t(8) = 2.57, p < .017 \), and \( t(11) = 3.13, p < .005 \).

In summary, there are indications that the eye movements are related to the observers’ psychophysical responses. In particular, for the “disparity-only” condition, the vergence responses are higher for “out-of-phase” responses as compared with “in-phase” responses. Further, the vergence response and the vergence slips for the “in-phase” responses increase more as compared with the “out-of-phase” responses, that is, a slope lower than 1. The results are consistent between the “all cues” and the “disparity-only” condition. There were no significant relationships between the eye movements for the two response categories in the “size-only” condition.

### Experiment 2

We were also interested in finding out whether the effect of eye movements on induced motion is specific for motion in depth or whether such an effect also exists in the frontoparallel plane for comparable retinal speeds and viewing conditions. We therefore designed a second experiment that made a direct comparison between
Figure 5. Example of the gains and the phase lags for the vergence data of observer J.H. The amplitudes of the vergence responses of all trials are shown as a function of the test amplitude for the three cue-type conditions in the left column. Phase lags are shown in the right column. We have plotted the phase lags in degrees: A phase lag of $-10$ degrees corresponds to a lag of 83 ms behind the target. The black data points are for the “eyes on inducer” condition, and the gray data points are for the “eyes on test” condition. The amplitudes of the inducer (0.75 degrees) and test targets (between $-0.4$ and 0 degrees, and from 0 to 0.4 degrees) are shown by straight lines.
induced motion in depth and induced motion in the frontoparallel plane.

**Method**

**Observers**
Two male and four female observers with ages ranging between 26 and 38 years participated in this experiment. Observers H.N. and J.H. also participated in Experiment 1. Observer V.D. was a semi-naive coworker and participated also in the control conditions of Experiment 1. The other observers were naive to the purpose of the experiment. Further particulars are as in Experiment 1.

**Materials**
As described in Experiment 1.

**Procedure**
In this experiment, we used the same experimental paradigm and procedure as in Experiment 1.

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<th>Observer</th>
<th>Version amplitude</th>
<th>Version phase lag</th>
<th>Vergence amplitude</th>
<th>Vergence phase lag</th>
<th>Version slip</th>
<th>Vergence slip</th>
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<td></td>
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<tr>
<td>S.A.</td>
<td>0.07 (0.09)</td>
<td>51.0 (110.6)</td>
<td>0.43 (0.08)</td>
<td>18.3 (6.5)</td>
<td>0.36 (0.08)</td>
<td></td>
</tr>
<tr>
<td>R.G.</td>
<td>0.05 (0.03)</td>
<td>87.6 (74.6)</td>
<td>0.54 (0.06)</td>
<td>15.0 (5.4)</td>
<td>0.26 (0.06)</td>
<td></td>
</tr>
<tr>
<td>L.H.</td>
<td>0.08 (0.04)</td>
<td>165.7 (80.0)</td>
<td>0.41 (0.10)</td>
<td>23.0 (12.9)</td>
<td>0.41 (0.10)</td>
<td></td>
</tr>
<tr>
<td>V.D.</td>
<td>0.08 (0.04)</td>
<td>157.8 (70.5)</td>
<td>0.65 (0.06)</td>
<td>15.6 (5.5)</td>
<td>0.21 (0.06)</td>
<td></td>
</tr>
<tr>
<td>C.D.</td>
<td>0.05 (0.03)</td>
<td>110.6 (104.7)</td>
<td>0.56 (0.08)</td>
<td>0.7 (5.11)</td>
<td>0.19 (0.06)</td>
<td></td>
</tr>
<tr>
<td>C.G.</td>
<td>0.03 (0.02)</td>
<td>68.7 (92.3)</td>
<td>0.58 (0.05)</td>
<td>10.0 (4.9)</td>
<td>0.20 (0.06)</td>
<td></td>
</tr>
<tr>
<td>All cues/in depth (half amplitude)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>H.N.</td>
<td>0.06 (0.04)</td>
<td>121.3 (94.1)</td>
<td>0.27 (0.04)</td>
<td>6.3 (12.3)</td>
<td>0.11 (0.05)</td>
<td></td>
</tr>
<tr>
<td>J.H.</td>
<td>0.03 (0.02)</td>
<td>92.2 (113.3)</td>
<td>0.27 (0.05)</td>
<td>7.6 (7.5)</td>
<td>0.11 (0.04)</td>
<td></td>
</tr>
<tr>
<td>A.C.</td>
<td>0.04 (0.03)</td>
<td>114.3 (100.6)</td>
<td>0.22 (0.04)</td>
<td>21.3 (8.2)</td>
<td>0.18 (0.04)</td>
<td></td>
</tr>
<tr>
<td>V.D.</td>
<td>0.05 (0.03)</td>
<td>102.8 (97.5)</td>
<td>0.30 (0.04)</td>
<td>12.7 (6.7)</td>
<td>0.10 (0.03)</td>
<td></td>
</tr>
<tr>
<td>Size only (binocular viewing)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>H.N.</td>
<td>0.06 (0.04)</td>
<td>109.0 (106.1)</td>
<td>0.06 (0.04)</td>
<td>33.0 (28.0)</td>
<td>–</td>
<td>–</td>
</tr>
<tr>
<td>J.H.</td>
<td>0.03 (0.03)</td>
<td>97.0 (102.8)</td>
<td>0.07 (0.05)</td>
<td>49.6 (66.1)</td>
<td>–</td>
<td>–</td>
</tr>
<tr>
<td>S.A.</td>
<td>0.08 (0.06)</td>
<td>90.8 (110.3)</td>
<td>0.09 (0.08)</td>
<td>33.1 (87.3)</td>
<td>–</td>
<td>–</td>
</tr>
<tr>
<td>R.G.</td>
<td>0.04 (0.02)</td>
<td>91.9 (89.2)</td>
<td>0.05 (0.03)</td>
<td>39.7 (71.8)</td>
<td>–</td>
<td>–</td>
</tr>
<tr>
<td>Size only (monocular viewing)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>H.N.</td>
<td>0.10 (0.06)</td>
<td>33.7 (86.7)</td>
<td>0.12 (0.07)</td>
<td>13.2 (31.0)</td>
<td>–</td>
<td>–</td>
</tr>
<tr>
<td>J.H.</td>
<td>0.10 (0.05)</td>
<td>37.1 (85.8)</td>
<td>0.16 (0.07)</td>
<td>5.3 (53.2)</td>
<td>–</td>
<td>–</td>
</tr>
<tr>
<td>A.C.</td>
<td>0.06 (0.05)</td>
<td>116.3 (85.1)</td>
<td>0.07 (0.05)</td>
<td>20.9 (93.6)</td>
<td>–</td>
<td>–</td>
</tr>
<tr>
<td>V.D.</td>
<td>0.07 (0.04)</td>
<td>16.2 (97.7)</td>
<td>0.12 (0.05)</td>
<td>45.9 (37.4)</td>
<td>–</td>
<td>–</td>
</tr>
<tr>
<td>Disparity only</td>
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<td></td>
<td></td>
<td></td>
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<td></td>
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<tr>
<td>H.N.</td>
<td>0.05 (0.03)</td>
<td>117.7 (99.5)</td>
<td>0.58 (0.05)</td>
<td>11.0 (5.9)</td>
<td>0.21 (0.06)</td>
<td></td>
</tr>
<tr>
<td>J.H.</td>
<td>0.05 (0.03)</td>
<td>71.9 (115.5)</td>
<td>0.58 (0.06)</td>
<td>7.8 (3.6)</td>
<td>0.19 (0.06)</td>
<td></td>
</tr>
<tr>
<td>S.A.</td>
<td>0.06 (0.04)</td>
<td>115.1 (117.8)</td>
<td>0.40 (0.09)</td>
<td>23.4 (11.9)</td>
<td>0.40 (0.09)</td>
<td></td>
</tr>
<tr>
<td>R.G.</td>
<td>0.05 (0.02)</td>
<td>77.9 (68.1)</td>
<td>0.51 (0.07)</td>
<td>15.5 (4.3)</td>
<td>0.29 (0.06)</td>
<td></td>
</tr>
<tr>
<td>Frontoparallel</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>H.N.</td>
<td>0.35 (0.06)</td>
<td>6.4 (9.2)</td>
<td>0.05 (0.04)</td>
<td>21.4 (106.3)</td>
<td>0.09 (0.05)</td>
<td></td>
</tr>
<tr>
<td>J.H.</td>
<td>0.30 (0.05)</td>
<td>4.6 (7.0)</td>
<td>0.03 (0.02)</td>
<td>12.7 (94.9)</td>
<td>0.09 (0.04)</td>
<td></td>
</tr>
<tr>
<td>L.H.</td>
<td>0.35 (0.05)</td>
<td>0.1 (11.7)</td>
<td>0.07 (0.06)</td>
<td>3.2 (103.0)</td>
<td>0.06 (0.05)</td>
<td></td>
</tr>
<tr>
<td>V.D.</td>
<td>0.38 (0.04)</td>
<td>4.3 (5.5)</td>
<td>0.04 (0.03)</td>
<td>14.1 (90.0)</td>
<td>0.05 (0.03)</td>
<td></td>
</tr>
<tr>
<td>C.D.</td>
<td>0.36 (0.06)</td>
<td>0.4 (9.0)</td>
<td>0.07 (0.06)</td>
<td>6.49 (88.1)</td>
<td>0.07 (0.04)</td>
<td></td>
</tr>
<tr>
<td>C.G.</td>
<td>0.37 (0.04)</td>
<td>8.7 (5.3)</td>
<td>0.04 (0.02)</td>
<td>33.4 (67.3)</td>
<td>0.07 (0.03)</td>
<td></td>
</tr>
</tbody>
</table>

Table 1. Summary of the eye movements for all observers (except J.B. for who eye movements could not be measured) in all experiments. All numbers are in degrees. In the size-only conditions, the version and vergence slips are the same as the eye movement measures because the stimulus does not move on screen; the stimulus only expands and contracts. Likewise, the version slip is the same as the version eye movement measures when the stimulus moves in depth, and the vergence slip is the same as the vergence movements when the stimulus only moves in the frontoparallel plane.
We used a $2 \times 2$ factorial design. The first factor, eye movement, has two levels, namely, “eyes on inducer” and “eyes on test.” The second factor, “motion,” has two levels, namely, “in depth” and “frontoparallel.” The “in-depth” condition is the same as the “all cues” condition in Experiment 1. The data for observers H.N. and J.H. for this condition are taken from Experiment 1. In the “frontoparallel” condition, the target dot does not move in depth but moves horizontally in the frontoparallel plane. The centers of oscillation of both targets are at a 1.0-m distance from the observer, as in the previous experiments. The stimulus configuration in this condition is also viewed with both eyes through the anaglyph glasses as in Experiment 1. The peak-to-peak amplitude of the inducer was 1.30 cm for frontoparallel motion, which corresponds to 44 arcmin of visual angle. This amplitude corresponds to the amplitude of the target in each half-image in the “in-depth” condition, that is, the amplitude of the target’s image in one eye.

We used nine different test amplitudes for the test target with equilinear spacing. Two different ranges were used depending on experimental condition because pilot results had shown that we could expect a considerable difference between different conditions; we used $35\%$, $26.25\%$, $17.5\%$, $8.75\%$, $0\%$, $8.75\%$, $17.5\%$, $26.25$, and $35\%$ of the inducer’s amplitude for the “eyes on test”/“in-depth” condition.

Figure 6. Panels A, B, and C are for the “all cues,” the “size-only,” and the “disparity-only conditions, respectively. The first column shows the mean vergence responses for trials in which the observer responded “in phase” plotted against the mean vergence responses for trials in which the observer responded “out of phase.” Each symbol of the same style is for different test amplitudes. We only used the test amplitudes for which the probability of responding “in phase” was between .25 and .75. Different symbol styles indicate different observers. Likewise, the middle column shows the mean phase lags for “in-phase” responses against “out-of-phase” responses. The left column shows the same for the vergence slip. The red line is the best-fitting straight line through the data points. The dotted black line is the line through the origin with slope 1. Different symbol styles indicate different observers.
condition and $-5\%, 3.75\%, 12.5\%, 21.25\%, 30\%$, $38.75\%, 47.5\%, 56.25\%$, and $65\%$ of the inducer’s amplitude in the other three conditions.

**Results**

**Psychophysics**

We analyzed the psychophysical data as in Experiment 1. The results of Experiment 2 are summarized in Figure 7. Rows A and B show data for the “in-depth” and the “frontoparallel” conditions, respectively. The three columns show, from left to right, the examples of psychometric functions for observer L. H., the biases, and the thresholds for all six observers. The “eyes on inducer” and the “eyes on test” are shown in dark and light gray.

We found that for the “in-depth” condition, the mean bias was $5.7\%$ ($SD = 7.2\%$) for the “eyes on test” and $36.0\%$ ($SD = 9.2\%$) for the “eyes on inducer” condition. The mean bias was different from zero for the “eyes on test” and “eyes on inducer” condition, $t(5) = 9.54$, $p < .001$, but not for the “eyes on test” condition. For the “frontoparallel” condition, we found that the mean biases were $23.3\%$ ($SD = 12.7\%$) and $43.6\%$ ($SD = 13.3\%$) for “eyes on test” and “eyes on inducer,” respectively. Both were significantly different from zero, $t(5) = 4.47$, $p < .007$, and $t(5) = 8.03$, $p < .001$, respectively.

We performed a $2 \times 2$ (Eye movement $\times$ Motion) repeated-measures ANOVA on the biases. We found a significant main effect for eye movement, $F(1,5) = 50.93$, $p < .001$, and for motion, $F(1,5) = 18.29$, $p < .008$. The interaction between eye movement and motion was not significant.

The mean discrimination thresholds for the “eyes on test” and the “eyes on inducer” were $3.8\%$ ($SD = 2.6\%$) and $14.2\%$ ($SD = 7.7\%$) for the “in-depth” condition. For the “frontoparallel” condition, the mean discrimination thresholds were $8.1\%$ ($SD = 2.6\%$) for “eyes on test” and $8.6\%$ ($SD = 5.6\%$) for “eyes on inducer.” We performed a $2 \times 2$ (Eye movement $\times$ Motion) repeated-measures ANOVA on the discrimination thresholds. This analysis did not reveal any significant main effects. There was a significant interaction effect between eye movement and motion, $F(1,5) = 8.62$, $p < .032$. None of the four subsequent $t$ tests to analyze this interaction were significant at an alpha level of $.05 / 4 = .125$.

We found that the size of induced motion was larger when the motion was frontoparallel than when the motion was in depth. Induced motion was larger when the eyes were kept on the inducer than when the eyes were kept on the test target.

Figure 7. Results for Experiment 2. The left most columns show examples of the psychometric functions for observer L.H. The middle column shows the bias, and the right column shows the discrimination thresholds for all observers. Row A shows the results for the “in-depth” condition; row B shows the results for the “frontoparallel” condition. Black lines and bars indicate the “eyes on inducer,” and the light gray lines and bars are for the “eyes on test” condition. Error bars show $\pm 1$ SD as calculated with Monte Carlo simulations.
Eye movements were analyzed as in Experiment 1. When the motion of the targets was in the frontoparallel plane, we looked at the version response. The version response is defined similarly to the vergence response described in Experiment 1, except that version is the mean of the viewing directions of the two eyes rather than the difference. Typical results are shown in Figure 8 for observer J.H. Figure 8A shows results for the “in-depth” conditions, and Figure 8B shows the results for the “frontoparallel” conditions. The upper panels in Figures 8A and 8B represent the vergence responses for all trials, and the lower panels describe the version responses. As expected, version is low for motion in depth and high for frontoparallel motion. Vice versa, the vergence response is low for frontoparallel motion and high for motion in depth.

Next, we looked at how the observers’ responses were related to their eye movements. We used the same procedure as in Experiment 1. In Figure 9, we plotted the mean vergence response, phase lag, and vergence slip for the two response categories against each other for the “in-depth” condition. For the “frontoparallel” condition, we used the version data rather than the vergence data. We also calculated the best-fitting line using a least-squares type II regression. There were no significant differences between any of the means for the two response categories. The slopes of the best-fitting line were also not statistically different from 1 at an alpha level of 5%. The finding in Experiment 1 that the slope of the best-fitting line through the vergence response...
data and the vergence slip for the two response categories in the “all cues” condition was different from 1 could not be replicated in this experiment.

**Discussion**

In Experiment 1, the nonzero biases when the eyes followed the inducer indicated that induced motion in depth resulted both when changing disparity was the only cue to motion in depth and when changing disparity was combined with a change in size of the targets on screen. When a change in size was the only cue to motion in depth, observer biases were close to zero. The inducer targets gave a clear impression of motion in depth, but the motion of the inducer target did not lead to a significant response bias to see the test target moving in the opposite direction to the inducer target. That is, a change in the size of the inducer on the screen did not induce motion in the test target. A first conclusion therefore is that induced motion in depth is not directly linked to the ultimate perception of motion in depth of the inducer target but to an earlier, preconscious stage in the visual processing of motion in depth.

We also found a large difference in the amount of induced motion as function of eye movement condition in Experiment 1. When the eyes followed the moving inducers, induced motion was up to 10 times larger than when the eyes were kept on the test target (whose motion was much smaller than that of the inducer). The effect of the eye movement condition was observed for the “all cues” and the “disparity-only” condition but not for the “size-only” condition. When looking at the discrimination thresholds, we observed an effect of eye movement and of cue condition. The interaction was also significant. Subsequent analyses of the interaction were not significant, but the difference between the two eye movement conditions in the size-only conditions approached significance closely.

In contrast to Farnè (1972), we did not find a significant amount of induced motion when size change was the only available cue for motion in depth. Due to the limited number of observers, we cannot of course conclude that there is no effect. A difference between this study and that of Farnè’s study is that Farnè used monocular viewing instead of binocular viewing. We have tested four observers with monocular viewing and again did not find significant induced motion in depth when size change was the only available cue. Note however that there are several reasons why the results of Farnè’s study cannot be generalized. For example, there is an instructional bias in Farnè’s study: He only asked a group of subjects to say whether there is induced motion in the stimulus shown, without comparing the results to those obtained with a stimulus without inducers moving in depth.

In contrast to this study, Gogel and Griffin (1982) and Likova and Tyler (2003) did not find an effect of eye movements on induced motion in depth. However, there are some notable differences between these studies and our own work. Foremost, there were more inducers in those earlier studies. They might have provided the observers with a reference frame that was sufficiently strong to abolish effects of eye movements. In Likova and Tyler’s study, the edges of the monitor could also be seen, which may have further suppressed the effects of eye movements. Likova and Tyler also used a repetitive two-frame motion stimulus. Observers saw an instantaneous jump in depth rather than the smooth motion used in our study. Gogel and Griffin used a combination of vertical motion and motion in depth. It is possible that these vertical eye movements were influencing the effect of induced motion just as the vergence movements did. It is also possible that there are two separate processes involved in generating induced motion in depth, namely, (1) a process that depends on the retinal stimulus and requires close proximity between inducer and test. Here, this process could be dominant when the test target is fixated. And (2) a second process that is related to a failure in vergence compensation, which does not depend on target separation. In our study, the separation between inducer and test target could be too large to activate the first mechanism when the test target is fixated, resulting in only a small, nonsignificant, induced motion in that fixation condition.

In the Experiment 2, we found that induced motion was also present for motion in the frontoparallel plane for equivalent retinal motion. There was a significant difference between motion in depth and frontoparallel motion, and there was also an effect of eye movement condition. Induced motion was larger in the frontoparallel condition as compared with the “in-depth” condition. Induced motion was larger when the eyes followed the inducer than when the eyes were kept relatively still on the test target. There was no significant interaction.

Gogel and Griffin’s study (1982) did seemingly find a difference between induced motion in depth and induced motion in the frontoparallel plane opposite to our results. In their case, however, induced motion and induced motion in the frontoparallel plane were both indicated by adjusting the orientation of a rod. The relative scaling of orientation angles between the depth direction and the frontoparallel direction was not known nor explored. A direct comparison is therefore not appropriate, and the Gogel and Griffin’s paper did not make conclusions about differences between induced motion in depth and induced motion in the frontoparallel plane. Our method relies on nulling induced motion and is a measure relative to the motion of the inducer, which does allow a direct comparison. Harris and German (2008) did not find a difference between induced motion in depth and in the frontoparallel plane for equivalent retinal motion. One of the differences between that work and the current study is
that the sizes of their targets were much smaller than that of ours. Because of the small size, looming was too small to be a cue to motion in depth. This might have resulted in a stronger induced motion in depth as explained below.

There are several potential explanations for our finding that induced motion is dependent upon which target the eyes are fixated on. The first possible explanation is in terms of the role of vergence in affecting the extent of induced motion. In the case when the observer fixates on the inducer, the eyes make a vergence movement, whereas the vergence response is very much smaller when the eyes are kept on the test target. In the case when the inducer is fixated, the image of the test target sweeps over the retina, whereas the retinal movement of the test target is close to zero when the eyes fixate on the test target. It is thought that the visual system derives an estimate of object motion from summing an extraretinal signal that represents the movement of the eyes and a retinal signal that represents the movement of the image of the stimulus on the retina (e.g., Freeman & Banks, 1998; Mack & Herman, 1973, 1978). An underregistration of the size of the physical eye movement made by the visual system relative to the registration of the physical retinal motion could result in the effects we observed here. In other words, there could be a gain difference between the extraretinal and the retinal signals. Note that the extraretinal gain factor is not the same as the physical gain of the eye movement relative to the stimulus; instead, it is a scalar to the signal that specifies how the eyes are moving. For example, in the extreme case that the extraretinal gain factor is zero and the physical gain factor is one, that is, the eyes are kept perfectly on the moving inducer, the eye movement signal is zero. In this extreme case, the perceived motion would rely entirely on the retinal motion. The inducer would thus be perceived as stationary because it does not move on the retina. The test stimulus would however be perceived as moving.

The underregistration of the eye movement signal is not 100% in the current experiments because the bias is not 100%. However, the extraretinal gain factor would nevertheless have to be substantially lower than the retinal gain to account for the results. Alternatively, as we suggested earlier, an equivalent explanation might be sought in a weighted contribution of absolute and relative retinal motion (Nefs & Harris, 2007). Our findings suggest therefore that observers' visual systems know more about their changes in vergence angle than was suggested by earlier work (e.g., Erkelens & Collewijn, 1985; Regan, Erkelens, & Collewijn, 1986). Regan et al. (1986) found that the absolute disparity of wide-angle stimuli could be changed by even up to 35 degrees without observers seeing any change in depth. This was suggestive of observers’ visual systems not having any idea about their state of vergence or about the changes in vergence as they happen. Presumably, the size of their stimuli revealed a bias toward large, nonlooming patterns being stable and thus overriding the information obtained from changes in vergence angle.

We found some indications in Experiment 1 that the observers’ responses were related to their eye movements in the “disparity-only” condition. There were no differences in the eye movements for the responses “in phase” and “out of phase” for the other two cue conditions. Also in Experiment 2, there were no significant differences. We did find that the slope of the best-fitting lines through the vergence data and the vergence slip data was significantly different from 1 in the “all cues” and the “disparity-only” conditions. The effect on the slope in the “all cues” condition could however not be replicated in Experiment 2, although the “all cues” and the “in depth” were the same. If there is a relationship between eye movements and observers’ response selection, the natural variance in the size of the eye movements for each observer is likely too small to reveal this reliably. That is, the difference between eye movements necessary to measure the psychophysical effect is not present in the set of eye movements. This does not mean that the observed difference in induced motion between “eyes on test” and “eyes on inducer” is not related to the eye movement. The variance in the amplitude of the vergence movements is much smaller than the size of the eye movement in the “eyes on inducer” (see Table 1) and might be too small to reveal this effect reliably in the present data set.

A second possible explanation is that the effects are created by variables that are associated with the eye movements. When an observer makes an eye movement when watching a moving object, several things that are closely associated with the eye movement change as well. For example, when the eyes move to follow a moving target, that target’s image stays at the same place on the retina, in the fovea. When the eyes are stationary, the inducer target’s image moves because of the vertical separation of the inducer and the test target in an area of lower spatial acuity and where luminance discrimination thresholds are lower (e.g., see Wyszecki & Stiles, 2000). However, the vertical separation of targets is necessary to avoid diplopia in either one of the targets. That is, if two targets have a smaller angular separation, Panum’s fusional area becomes extremely small (e.g., see Howard & Rogers, 2002). The current data do not dissociate the underlying reasons why eye movement has an effect on induced motion. We speculate that it is not the eye motion as a muscular event, but whether one can see the change in retinal size clearly, that is the important issue. In other words, a clear image of a target that does not change in size attenuates induced motion in depth when it is clearly seen in the fovea. When the change in target size cannot be seen clearly, induced motion in depth is not suppressed. This explanation may also account for Gogel and Griffin’s (1982) and Harris and German’s (2008) data.

Apparently, the change in the total amount of light impinging from the target on the retina does not suppress this effect, although luminance discrimination thresholds are lower in the parafovea. The link between size change and disparity change is well known. For example, it is
well known that targets that change their disparity but keep their retinal size constant are perceived as changing in size in physical space (Regan et al., 1986).

A third possibility is an effect of vergence slip. The vergence responses are in general not 100%. In the condition when the eyes are kept on the inducer, both the inducer target and the test target move slightly out of fixation during the motion due to vergence slip. This creates a fixation disparity for the inducer target. When the eyes are kept on the test pattern, the target stays in the same place in the fovea and thus does not have fixation disparity.

In summary, we reported two experiments that evaluated the effectiveness of different cues for inducing motion in depth and how they interact with eye movements. We found a large effect of eye movements on the size of induced motion when binocular disparity was involved but not when size change was the only cue. We speculate that the eye movements might cause these effects themselves, or alternatively that the variables that are associated with these eye movements such as the ability to see the targets change in size, or vergence slip, are responsible. Irrespective of the explanation, we have shown that induced motion in the depth dimension is highly dependent on the orientation and/or the movement of the eyes with respect to the stimulus.

Acknowledgments

This research was supported by an EPSRC Advanced Fellowship to J.M.H.

Commercial relationships: none.

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Footnote

1Sinusoidal motion in real 3D space results in a slightly off-sinusoidal motion when expressed in units of angular binocular parallax (see the Eye movements section).

References


