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A Trajectory Illusion and Its Relation to Induced Motion and Smooth Pursuit Eye Movements

Nancy Shima Wada

A Thesis

in

The Department

of

Psychology

Presented in Partial Fulfillment of the Requirements
for the Degree of Master of Arts at
Concordia University
Montréal, Québec, Canada

August 2001

0-612-64023-X

Abstract

A Trajectory Illusion and Its Relation to Induced Motion and Smooth Pursuit Eye Movements

Nancy S. Wada

Navigation in the environment relies, in part, on the visual system to differentiate self-motion from that of other objects. Research examining the way in which the brain is able to visually disentangle forward locomotion from eye motion, for example, suggests that the brain may have an eye movement compensation mechanism. Other findings, however, question the existence of this mechanism in that the previously reported illusory shift in the focus of expansion (FOE) may be due to induced motion. Yet, this alternative hypothesis may need to be revised in order to account for the perception of straight, radial trajectories as curved. In order to understand the conditions under which this trajectory illusion exists, the current investigation examined the role of induced motion, radial speed gradient, and smooth pursuit eye movements (SPEM). Results suggest that the strength of the illusion relies on induced motion and SPEMs, thereby implicating that the role of eye movements in the illusory FOE shift needs to be taken into consideration.

Acknowledgements

Many thanks go to my supervisor, Dr. Michael von Grünau, for his support throughout the development of this research endeavor. A special thanks goes to Drs. Rick Gurnsey, Michael Bross, and César Galera for their invaluable comments and suggestions, and to my participants for unselfishly devoting their time and energy to this project.

Last, but not least, my heartfelt appreciation goes to my parents, Kay and Steve Wada, and to my sister, Lucy Wada, for their unconditional love and support. Thank you for making me laugh, for providing a listening ear, and, most of all, for believing in me. You are my source of strength and inspiration, and I dedicate this thesis to you.

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A Trajectory Illusion and Its Relation to Induced Motion and Smooth Pursuit Eye Movements

How does an observer navigate in the environment without colliding with other objects? The answer lies in the brain's ability to monitor and integrate self-movement with the movement of other objects (van den Berg, 2000). While the brain uses information from various sources such as the vestibular, kinesthetic, and auditory systems to perform these tasks, it also relies on information from the visual system to indicate where in space the body, head, and eyes are in relation to other objects (van den Berg, 2000; Warren, 1995; Coren, Ward, & Enns, 1994). In other words, one way in which the brain is able to integrate self-movement with the movement of other objects is by utilizing the information available from the visual environment (Wexler, Paneral, Lamouret, & Droulez, 2001).

As an observer moves forward in space, he/she perceives the surrounding environment to move past him/her in a radial pattern -- referred to as 'optic flow' (Gibson, 1966; van den Berg, 2000; Iordanova & von Grünau, in press). Objects in this environment not only increase in size as the distance between them and the observer decreases, but the speed with which they move also increases. In addition, the point from which objects appear to emanate, referred to as the focus of expansion (FOE), and towards which the observer's body is heading overlap during forward movement in space, that is, provided that the observer's eyes are stationary and face the direction in which he/she is heading. In other words, optic flow contains information not only about the distance of objects from the observer, but also about the direction in which the observer is heading (Warren, 1995).

The brain's ability to extract optic flow information is complicated by the fact that the observer's eyes also move, and their position may not necessarily coincide with the body's direction of movement (van den Berg, 2000; Lappe & Hoffman, 2000; Warren, 1995; Iordanova & von Grünau, in press). Under conditions of forward locomotion without eye movements, objects in the visual environment accelerate from the center to the periphery of the retina, thereby forming an expanding, radial optic flow pattern that also corresponds to heading direction. However, if an observer, during forward locomotion, pursues a rightward-moving object with his eyes, thereby adding leftward motion to the expanding motion of all non-tracked objects in the visual environment, the point towards which the body is heading, and the point from which objects emanate no longer overlap (see Figure 1). In other words, the FOE does not

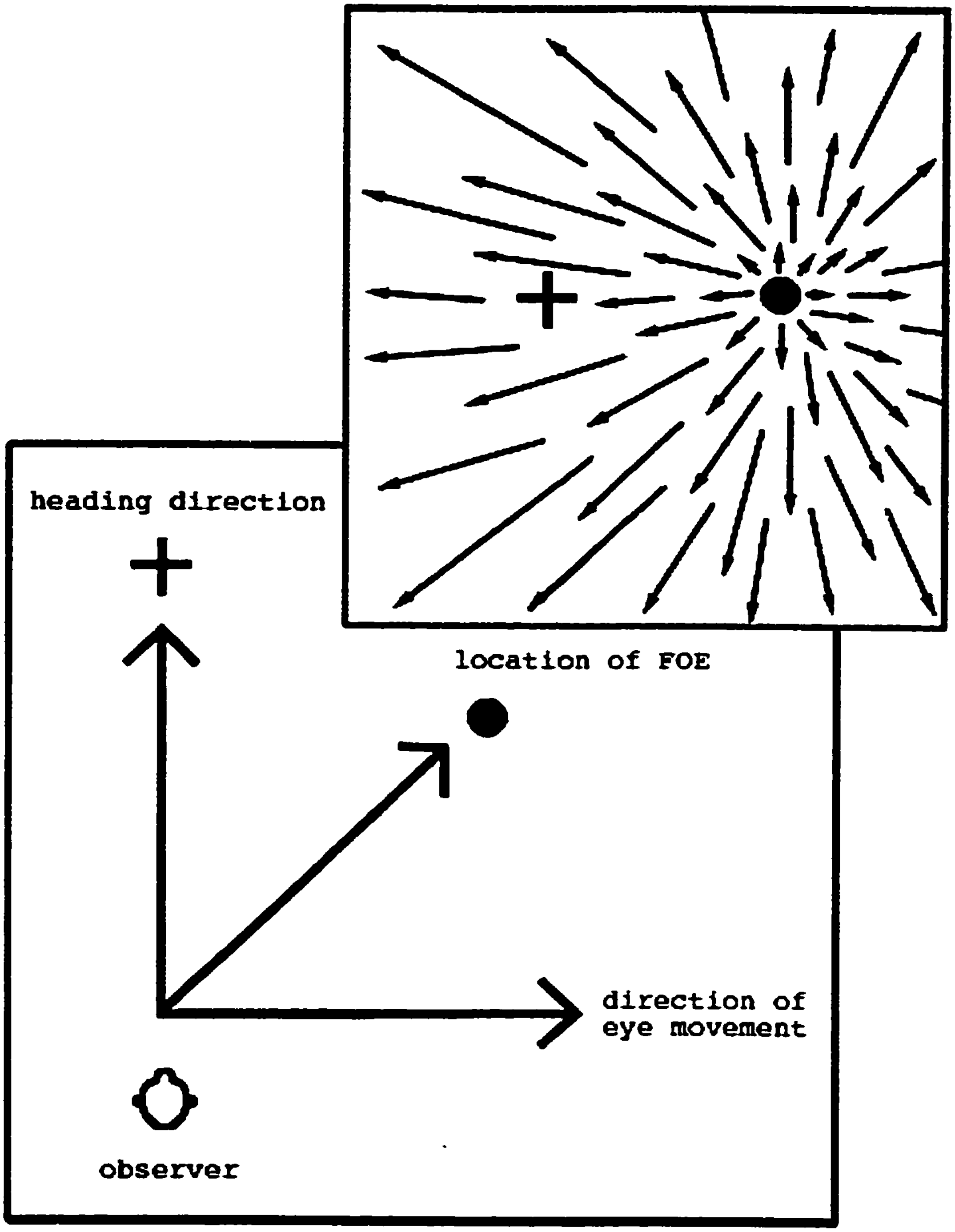


Figure 1. Example of heading direction not corresponding to the location of the focus of expansion (FOE).

correspond to heading direction, and, as a result, the optic flow pattern is no longer symmetrical (Warren, 1995).

Yet, despite the fact that the direction of the eyes does not always correspond with that of the body, an observer is still able to correctly identify the direction in which he is heading. Evidence seems to suggest that the brain may be able to disregard, or compensate for, any distortion in the forward-motion caused by, in this case, horizontal eye movements through the use of extraretinal or oculomotor signals (Warren, 1995). Specifically, when presented with a display containing a single, frontal plane and a moving fixation point, observers were able to accurately detect the direction in which they were heading when they actively followed the moving fixation point, but not when they passively watched a simulation of the optical flow pattern produced by such an eye movement (Warren, 1995). In other words, under these circumstances, observers were able to decompose the environment into radial motion relating to forward self-motion and into planar motion relating to pursuit eye movements only when their eyes actually moved (Iordanova & von Grünau, in press).

Without this extraretinal compensation, however, an observer may still, to some extent, be able to visually decompose a stimulus into its radial and planar motion components. In fact, evidence seems to suggest that visual information about optic flow is "sufficient [by itself] for decomposition" when the environment contains depth-rich cues such as disparity or texture (Warren, 1995, 1998).

Alternatively, instead of assessing the conditions under which observers are able to visually discriminate the direction of heading from that of an eye movement, one can also examine how the brain incorporates radial and planar motion components that are physically decomposed. When presented with a stimulus consisting of a field of expanding radial dots with a central FOE, and a separate, transparently superimposed field of planar, or horizontally-moving, dots, observers judged the FOE as being shifted in the direction of the planar motion (Duffy & Wurtz, 1993). Duffy and Wurtz (1993) hypothesized that this illusory shift of the FOE may be attributed to a visual compensation mechanism where the goal of this mechanism is to counteract the motion resulting from an eye movement. For example, if an observer's eyes move to the right, producing leftward motion, the FOE will also shift to the right. The visual compensation mechanism, in an attempt to disregard any distortion of the radial motion caused by this rightward eye movement and, therefore, rightward FOE shift, will shift the FOE leftward. Due to the fact that the FOE of the radial motion in Duffy and Wurtz's (1993) stimulus is not shifted, the leftward shift by the visual compensation mechanism results in an illusory, leftward FOE shift.

Whereas the explanation offered by Duffy & Wurtz (1993, 1995) emphasizes the role of a hypothetical brain mechanism in eliciting the illusory FOE shift (top-down process), the explanation offered by Meese, Smith, and Harris (1995) places importance on a particular characteristic of the visual stimulus (bottom-up process). Specifically, Meese et al. (1995) postulated that the illusory FOE shift was due to induced motion -- the appearance of "a stationary target...[moving] in [the] direction opposite that of a surrounding object" (Pack & Mingolla, 1998). According to the induced motion hypothesis, leftward planar motion, for example, induces each radial dot to shift slightly to the right. This rightward shift added to radial motion is thought to produce the illusory, leftward FOE shift (see Figure 2).

Although the induced motion hypothesis appears to accurately describe the illusory FOE shift, it fails to consider the contribution of the speed gradient belonging to the radial motion. Specifically, the question that

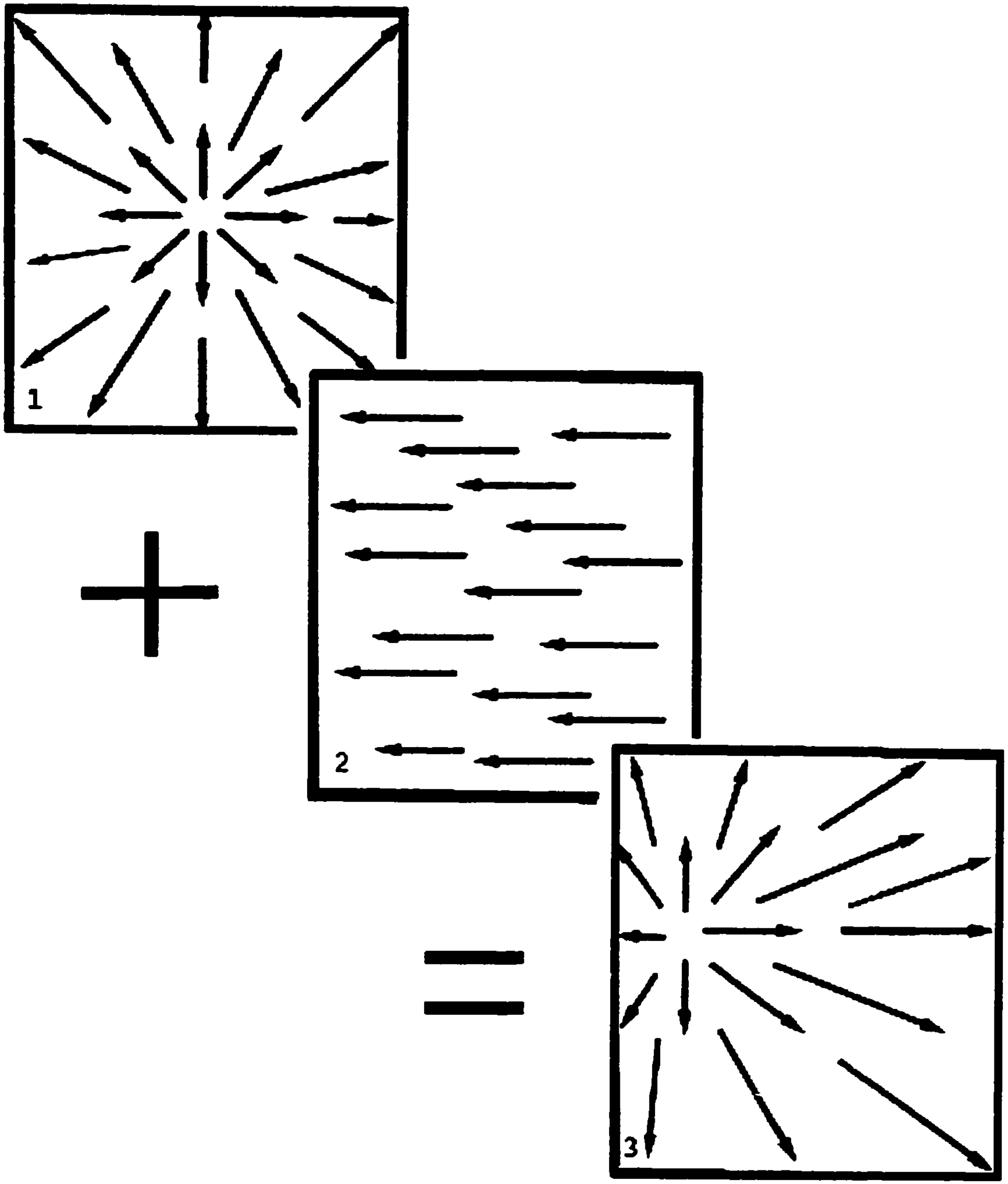


Figure 2. Example of induced motion contributing to the illusory FOE shift.

remains concerns the degree to which the speed of the radial motion in relation to that of the planar motion is responsible for the illusory FOE shift. In fact, evidence seems to suggest that stimulus speed affects the degree to which induced motion is effective (Wallach & Becklen, 1983; Becklen & Wallach, 1985; German & Harris, 2001). In a series of experiments examining the effect of speed on induced motion, Wallach and Becklen (1983) found that increasing the speed of an oscillatory, horizontally-moving pattern of vertical lines reduced its inducing effect on an equally fast oscillatory, vertically-moving, pursued target dot. In other words, the width of the target's illusory, elliptical path -- the extent to which the target was horizontally displaced -- diminished as the speed of both the pattern and the target increased. This reduction of horizontal displacement also occurred when the horizontally-moving pattern consisted of random dots, and when the target was not pursued by the eyes (Becklen & Wallach, 1985). In other words, this effect seems to be particular to induced motion, and occurs regardless of type of eye movements.

The implication of these findings is that a general inducing effect of the background planar dots may not entirely explain the illusory FOE shift. In other words, the inducing effect of the background planar dots may vary as a function of radial dot speed. The prediction is that as the speed of the radial dots increases, the inducing effect of the background planar dots should diminish. In other words, for each individual radial dot, the strongest horizontal displacement should occur near the FOE, and the least displacement should occur in the periphery.

Observations from pilot studies of the current investigation are consistent with this speed-dependent induced motion hypothesis. When tracked by the eyes, an accelerating radial dot with a straight trajectory initially appears to move in the direction opposite of the planar motion. However, as the radial dot accelerates in relation to the constant speed of the planar dots, it appears to swing around, and 'catch up' to its veridical trajectory (see Figure 3). Interestingly, this trajectory illusion also seems to be more pronounced for radial dots that move 'with' or perpendicular to the planar flow than for those that move 'against' the planar flow (see Figure 4).

The problem arises in that there have been no reports of such a trajectory illusion in the illusory FOE shift literature. One possibility is that this trajectory illusion exists, but has not been measured due to the

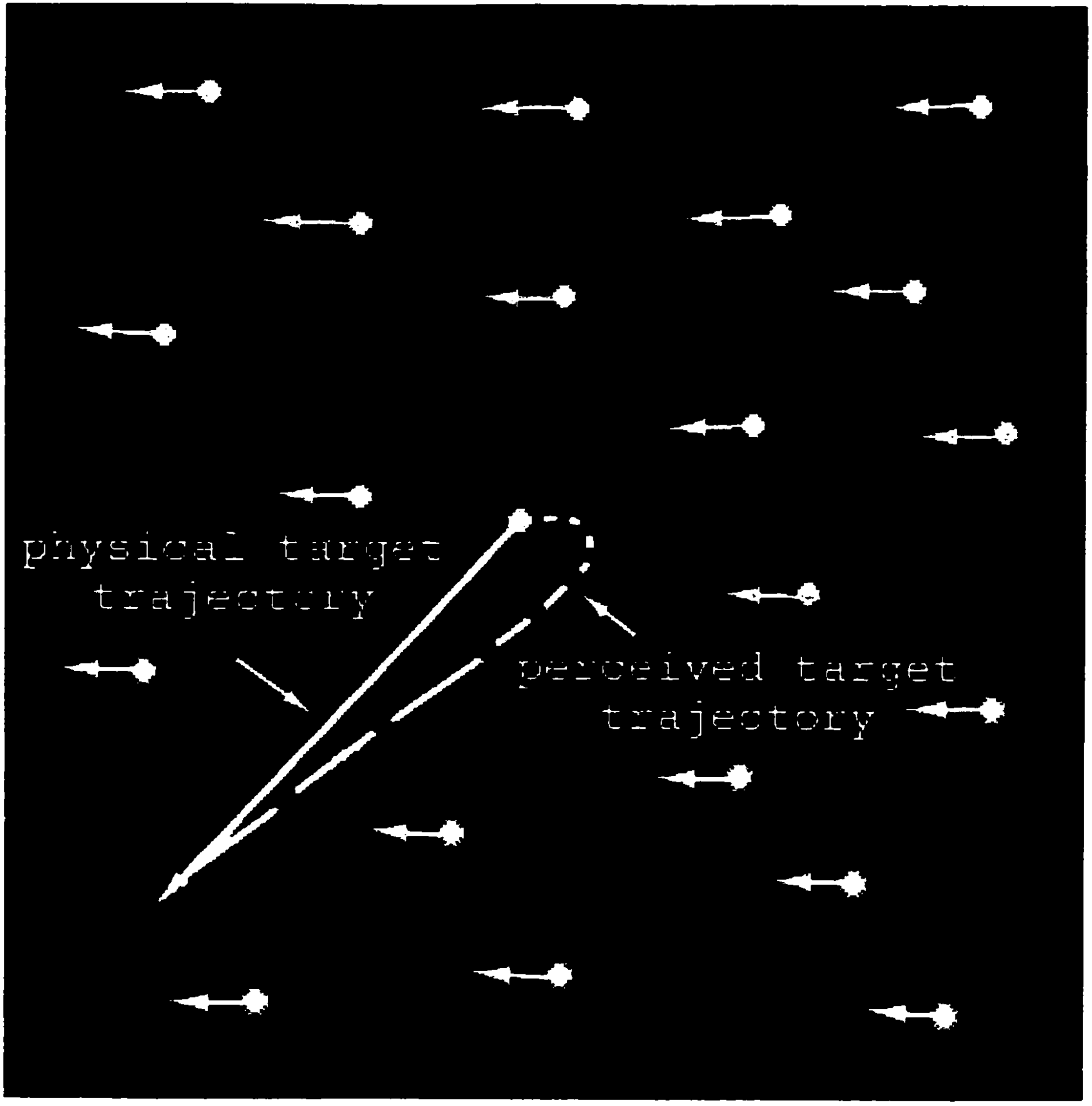


Figure 3. Example of a straight target trajectory appearing curved.

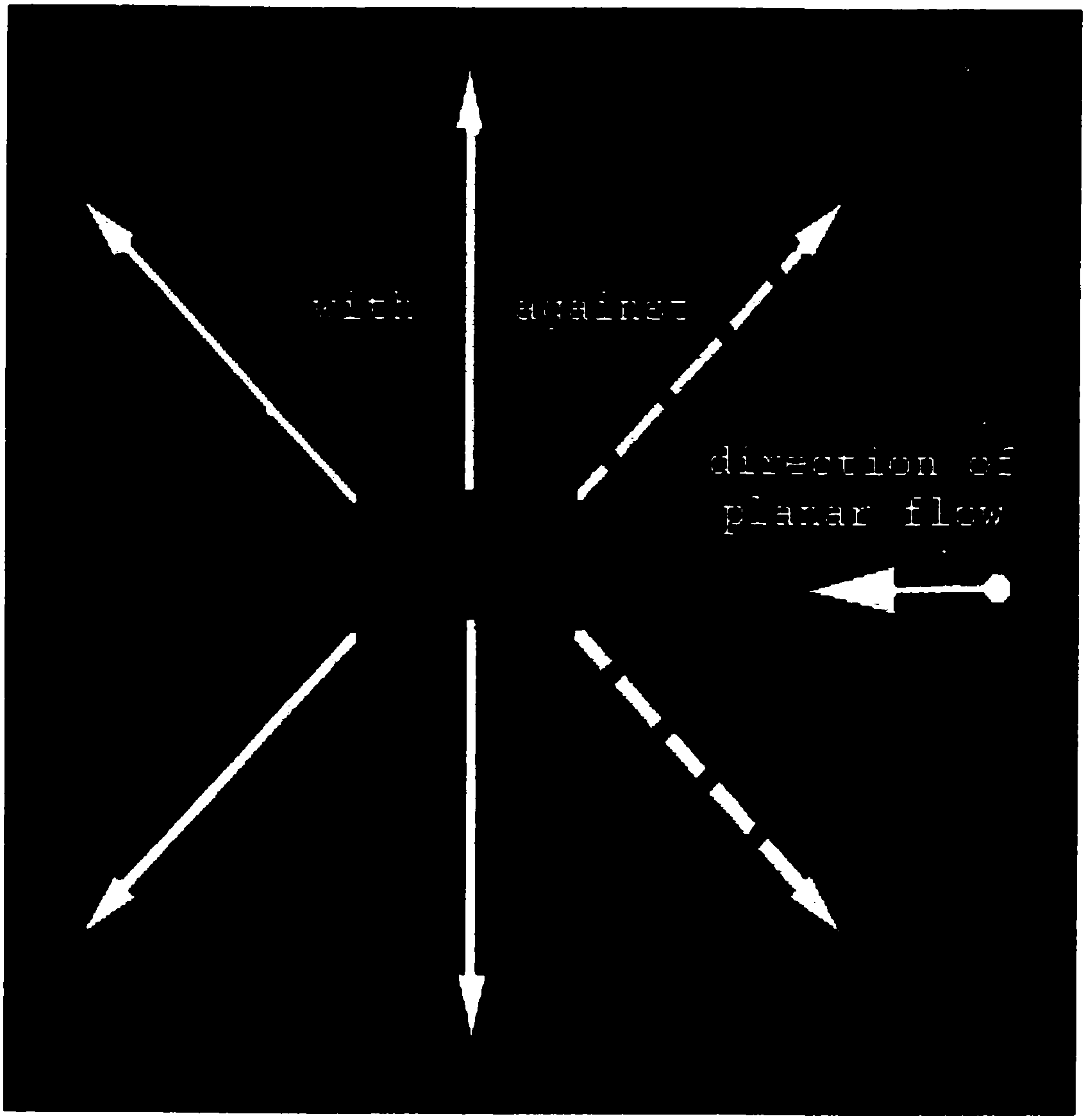


Figure 4. Example of target trajectories moving 'with' or 'against' the direction of planar flow.

nature of the FOE task. Another possibility is that the trajectory illusion may be due to smooth pursuit eye movements (SPEMs) -- eye movements that result from tracking a moving object (Carpenter, 1988; Rashbass, 1961; Ilg, 1997). A third possibility is that the trajectory illusion may have contributions from both induced motion and SPEMs. Although increased speeds reduced the effectiveness of induced motion regardless of the type of eye movement, Belken & Wallach (1985) noted that the extent of induced motion for the stationary fixation condition was approximately half of that for the pursuit condition across all stimulus speeds. In other words, induced motion was less effective when fixating on a stationary dot than when pursuing the target dot.

Evidence in the eye movement literature is consistent with the idea that the system controlling SPEMs may be responsible for the trajectory illusion, or may increase the extent to which an object is induced to move, that is, compared to when that same object is viewed under stationary fixation. Specifically, the findings indicate that SPEMs lead to an underestimation of the target's position and velocity (Festinger, Sedgwick, & Holtzman, 1976; Mack & Herman, 1972; Honda, 1990; Festinger & Easton, 1974; Stone, Beutter, & Lorenceau, 1996; Turano &

Heidenreich, 1996). Festinger et al. (1976) observed that the perceived extent of a tracked target's displacement was consistently less than the target's actual displacement. Similarly, Mack and Herman (1972) reported that not only was a tracked target's extent of displacement underestimated compared to that of an untracked target, but so was the target's speed (Aubert-Fleischl phenomenon).

Evidence also suggests that SPEMs alter the perception of both the position and velocity of surrounding background objects (Wertheim & Van Gelder, 1990). Mack and Herman (1973, 1978) observed that pursuit of a target, compared to central fixation, resulted in stationary surrounding objects being perceived to move in the direction opposite to that of the target. Often referred to as the Filehne illusion (Mack & Herman, 1973, 1978; de Graaf & Wertheim, 1988; Haarmeier, Thier, Repnow, & Petersen, 1997), this finding is thought to indicate that the visual system is not able to completely compensate for SPEMs, thereby resulting in a partial position constancy loss of the surrounding objects. Similarly, Turano and Heidenreich (1999) found that the perceived speed of the background stimulus slowed or quickened as a function of the direction of pursuit. In other words, had the visual system been able to compensate fully for SPEMs, the perceived speed of the background stimulus under pursuit conditions would not have differed from that of the background stimulus under stationary fixation.

Also consistent with the idea that SPEMs may play a role in the illusory FOE shift are neurophysiological findings that suggest that the systems controlling SPEM and motion perception are closely intertwined. Specifically, neurons of the middle temporal (MT) and the medial superior temporal (MST) cortices, two areas important for motion perception, have also been shown to fire during pursuit -- even in the absence of a visual target (Komatsu & Wurtz, 1988; Newsome, Britten, Salzman, & Movshon, 1990; Wurtz, Yamasaki, Duffy, & Roy, 1990; Movshon, Lisberger, & Krauzlis, 1990). Similarly, lesions in MT and MST not only lead to deficits in motion processing, but also to pursuit initiation and maintenance (Newsome et al, 1990; Lisberger, Morris, & Tychsen, 1987). Conversely, electrical microstimulation in these areas modulates the responses of both direction-selective and pursuit neurons (Newsome et al., 1990; Komatsu & Wurtz, 1989). Specifically, stimulation of neurons in these areas results in a bias in favour of the preferred direction of these neurons or toward the side of brain stimulated, that is, regardless of the direction of the moving stimulus or of the pursuit eye movement (Newsome et al., 1990; Komatsu & Wurtz, 1989).

Taking into consideration that several explanations for the trajectory illusion exist, the current investigation aims to disentangle the contribution of each explanation from the others. Specifically, the purpose of this investigation is to determine the extent to which the trajectory illusion is due to speed-dependent induced motion, to smooth pursuit eye movements, or to both. If the trajectory illusion is a result of speed-dependent induced motion, then the presence or strength of the illusion -- operationally defined as the average response value chosen by observers -- will depend on the speed gradient of the radial dot. In other words, the trajectory illusion should be more pronounced in those situations in which the radial dot speed increases or decreases, and less so when its speed remains constant. Similarly, the trajectory illusion should disappear when the inducing, background planar dots are absent, that is, if induced motion is responsible for the trajectory illusion. However, if the trajectory illusion is a result of smooth pursuit eye movements, then the presence of the illusion, regardless of the radial speed gradient or of the presence of the inducing background, should disappear under stationary fixation. Of particular interest is whether pursuit of the radial dot is a necessary condition in eliciting the trajectory illusion.

Alternatively, the trajectory illusion could be the result of a combination of induced motion and smooth pursuit eye movements. Specifically, based on the findings of Becklen & Wallach (1985), the contributions of induced motion and smooth pursuit eye movements may be additive. In other words, a straight trajectory may be perceived as curved under stationary fixation, but may be perceived as increasingly more curved under conditions of smooth pursuit.

Experiment 1

This experiment sets out to answer two questions. First, it formally examines whether observers perceive a straight trajectory as curved. Second, it aims to disentangle the factors that may be the source(s) of this trajectory illusion.

Method

Participants

Six trained psychophysical observers between the ages of 23 and 56 participated in all conditions of Experiment 1. Four of the six observers were naive to the purpose of the experiment, and of the six, two were male and four were female.

Apparatus

A G4 Macintosh computer was used to generate the stimuli, and a 21" Sony monitor was used to display the stimuli at a resolution of 1024 x 768 pixels with a refresh rate of 85Hz. Participants sat at a distance of 57cm from the monitor with the position of their heads stabilized using a chin rest. All conditions of Experiment 1 were conducted under dim illumination.

Stimuli

Target dot. A white dot with a diameter of 0.2 degrees of visual angle was presented in the center of the screen, and always moved from its central position towards the periphery in one of four directions (clockwise from the top: 0, 180, 225, or 315 degrees). The manner in which the target dot moved followed either a straight or curved trajectory, and could accelerate, decelerate, or move with a constant velocity. Of the target dots that followed a curved path, their trajectories were created with the intention of mimicking the perception of illusory trajectories -- as determined from pilot studies of the current investigation, and were randomly presented with the straight, test trials.

Target speed gradient. Accelerating, decelerating, and constant-velocity target speed gradients were created using the following formula:

$$P = R(t/2)^r , \quad 0 \leq t \leq 2 \qquad (1)$$

where P is the position of the target dot from the center in polar coordinate space for a particular point in time, R is the end radius reached by the target dot (11.5 degrees for the cardinal directions and 15.3 degrees for the diagonal directions), t is time in seconds (from 0 to 2), and r is the rate at which the target position changed (3, 1/3, and 1 for accelerating, decelerating, and constant-velocity target speed gradients, respectively).

Target velocity. The instantaneous velocity of the accelerating, decelerating, and constant-velocity target dots was calculated using the following formula:

$$V = \partial P/\partial t = mt^{r-1}\ ,\ 0 \leq t \leq 2 \qquad (2)$$

where V is the velocity of the target dot for a particular point in time, $\partial P/\partial t$ is the derivative of Equation 1, m is the velocity constant (4.31, 3.04, and 5.75 for accelerating, decelerating, and constant-velocity target dots moving in one of the two cardinal directions; 5.74, 4.05, and 7.65 for accelerating, decelerating, and constant-velocity target dots moving in one of the two diagonal directions), t is time in seconds, and r is the rate at which the target position changed (3, 1/3, and 1 for accelerating, decelerating, and constant-velocity target speed gradients, respectively).

Target acceleration. The rate at which the target dots accelerated or decelerated was calculated using the following formula:

$$A = \partial V/\partial t = nt^{r-2}\ ,\ 0 \leq t \leq 2 \qquad (3)$$

where A is the acceleration of the target dot for a particular point in time, $\partial V/\partial t$ is the derivative of Equation 2, n is the acceleration constant (8.63 and -2.03 for accelerating and decelerating target dots moving in one of the two cardinal directions; 11.48 and -2.70 for accelerating and decelerating target dots moving in one of the two diagonal directions), t is time in seconds, and r is the rate at which the target position changed (3 and 1/3 for accelerating and decelerating target speed gradients, respectively).

Angle of target rotation. The angle of rotation was constant over time for accelerating, decelerating, and constant-velocity target dots moving along a straight path (clockwise from the top: 0, 180, 225, or 315 degrees). The angle of rotation varied with time for accelerating, decelerating, and constant-velocity target dots moving along a curved trajectory, and their position for a particular point in time was calculated using the following formula:

$$\theta = \alpha_a (t/2) \ , \ 0 \leq t \leq 2 \qquad (4)$$

where θ is the angular position of the target dot in polar coordinate space for a particular point in time, α is the 'end' angle of rotation reached by the target dot, a is the value indicating whether rotation began at the right of center and moved counterclockwise or at the top and moved clockwise (CCW and CW, respectively), and t is the time in seconds.

For curved target trajectories moving in one of the two cardinal directions, α_{CCW} was ±75 for the accelerating speed gradient, and α_{CW} was ±7 for both the decelerating and constant-velocity speed gradients. Of those curved target trajectories moving in one of the two diagonal directions, α_{CW} was ±45 for the accelerating speed gradient and α_{CCW} was ±45 for both the decelerating and constant-velocity speed gradients. Based on preliminary observations, these values of α were chosen to create physically curved trajectories that were comparable to the illusory trajectories perceived.

Velocity of angle rotation. The velocity of angle rotation was calculated using the following formula:

$$\beta = \partial\theta/\partial t = \alpha/2 \tag{5}$$

where β is the angular velocity of the target dot, $\partial\theta/\partial t$ is the derivative of Equation 4, and α is the 'end' angle of rotation reached by the target dot.

Background planar dots. Each target dot was presented with or without a field of 100 white, horizontal-moving dots covering a region of 23 deg^2. Each dot in the field had a diameter of 0.2 degrees of visual angle, and moved leftwards with a speed of 6.0 °/s. The onset of background dot movement always coincided with that of the target dot.

Type of fixation. Each target dot was also viewed under three conditions. In the Track Target condition, when the central, red fixation dot turned white, observers were asked to follow the white dot. In the Track Planar condition, observers were instructed to follow the peripheral, red fixation dot that was initially presented 2 degrees above and 11.5 degrees to the right of the center of the screen. The speed with which the peripheral fixation dot moved leftwards was 5.8 °/s, and its onset of movement coincided with that of the target dot. In the Fixate Center condition, a stationary, red fixation dot was presented in the center of the screen, and observers were asked to maintain fixation on this central dot for the duration of the trial.

Design

Experiment 1 consisted of three testing sessions. One testing session corresponded to one type of fixation, and the order in which observers fixated on the target, on the designated planar dot, or on a central, stationary dot was randomly assigned. Within each testing session, 6 conditions were presented -- two of which corresponded to a particular target speed gradient. Although the order in which the target speed gradients were presented was random, the Background Present condition of a particular target speed gradient always preceded the Background Absent condition for that same target speed gradient. The rationale for presenting the conditions in this order was to add some uncertainty as to whether a target trajectory was physically straight or curved. Within a single condition, the direction in which the target travelled and the path that the target followed were randomly assigned. There were 10 trials per type of target dot for a total of 80 trials per condition or 480 trials per testing session.

Procedure

Upon pressing the spacebar, observers were asked to fixate on a red dot that appeared in the center of the screen until it turned white, until the second fixation dot appeared, or until the trial was over. At the end of the stimulus presentation, examples of possible trajectories were displayed on the screen, and observers were always asked to rate the degree to which the target dot's trajectory appeared curved (see Figure 5). Based on preliminary observations of the current investigation, the

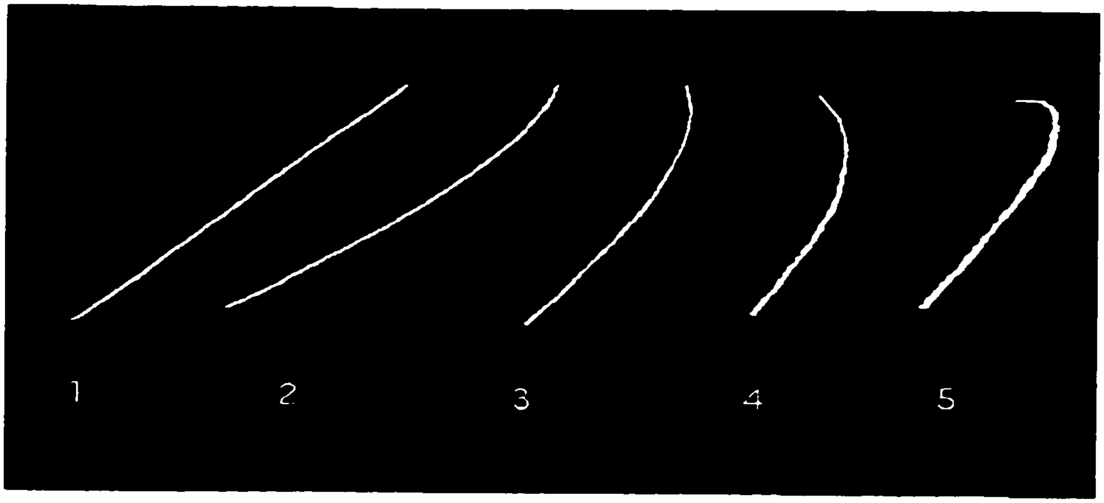


Figure 5. Example of response options provided to observers after tracking an accelerating target dot.

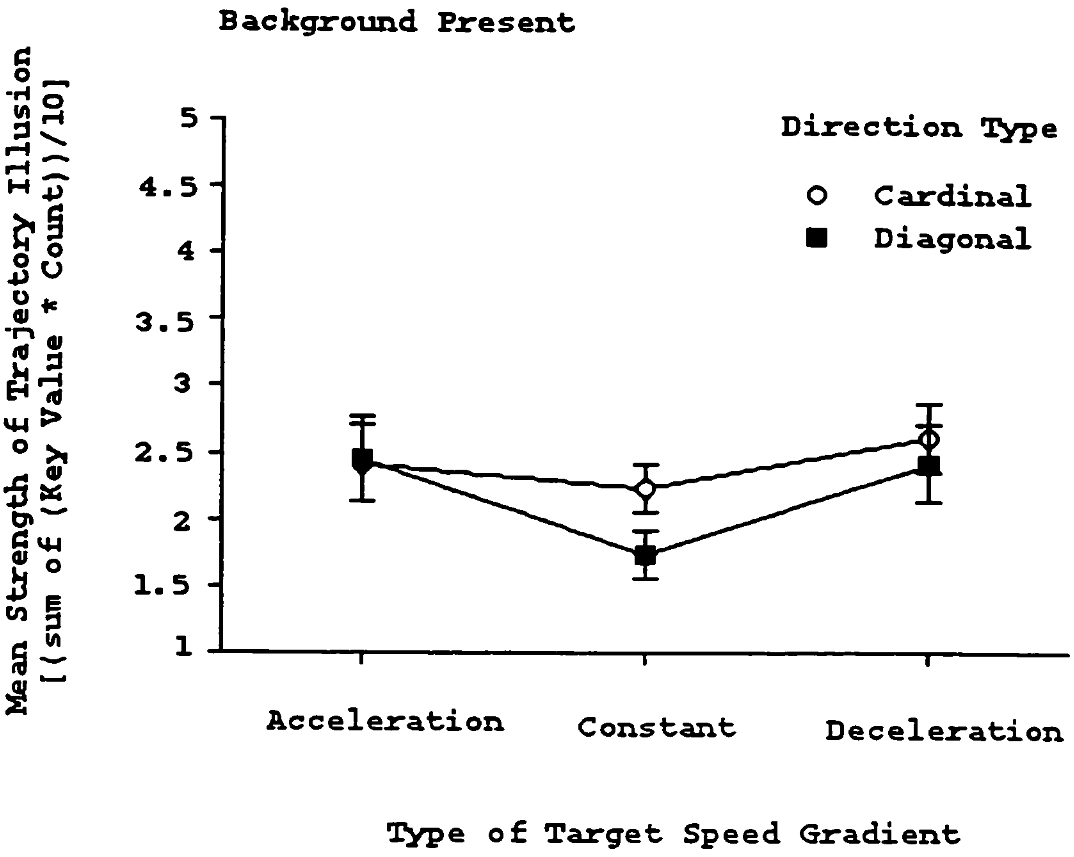
examples provided to observers were tailored to the direction and to the speed gradient of the target dot. Regardless of target direction and speed gradient, a value of 1 always corresponded to no curvature perceived, and a value of 5 always corresponded to a large degree of curvature perceived. After typing in the number that best corresponded to their perception, observers pressed the spacebar to view the next trial.

Results

For each condition of the experiment, the response values chosen by a particular observer to reflect the strength of the trajectory illusion were averaged, and the mean scores obtained for each observer were used in the statistical analyses.

Analyses of the interaction between type of fixation, type of target speed gradient, and type of background presented were separated by target direction. The rationale for splitting the analyses in this manner was due to the target speed of the cardinal directions being slower than that of the diagonal directions. The implication of such a difference in overall speed, according to the speed-induced motion hypothesis, is that the inducing background motion will have less of an effect on the faster than on the slower target velocities. In other words, should induced motion contribute to the perception of straight trajectories as curved, its effect will be subdued or masked for faster target velocities and enhanced for slower target velocities. In fact, detailed analyses of the statistically significant interaction between target direction and radial speed gradient, $F\ (2,\ 10) = 5.549$, $p < 0.05$ (see Appendix A), revealed that the constant-velocity, slower-moving, cardinal directions were more influenced by the inducing background motion than the constant-velocity, faster-moving, diagonal directions, _F_ (2, 10) = 19.297, $p < 0.0167$ (see Figure 6). Consistent with this argument is the finding that the interaction between target direction and radial speed gradient when the background was absent was not statistically significant, _F_ (2, 10) = 2.795, $p > 0.05$ (see Figure 7). Due to the fact that the sphericity assumption for repeated-measure designs was violated, and that multiple post-hoc tests were performed, the degrees of freedom and alpha level to which the obtained results were compared were altered using the Huynh-Feldt adjustment and Bonferroni correction factor, respectively. As needed, these Type I error adjustments were applied to subsequent analyses.

Cardinal directions (0 and 180 degrees). The statistically significant interaction between type of background presented and type of fixation is not only consistent with preliminary observations of straight trajectories appearing curved, but it is also consistent with the hypothesis that the trajectory illusion is dependent on both induced motion and on eye movements, _F_ (2, 10) = 2.48, $p < 0.05$ (see Figure 8). Detailed analyses of the interaction revealed that the decrease in strength of illusory reports from Background Present to Absent



<u>Figure 6</u>. Statistically significant interaction between Target Speed Gradient and Target Direction for Background Present condition.

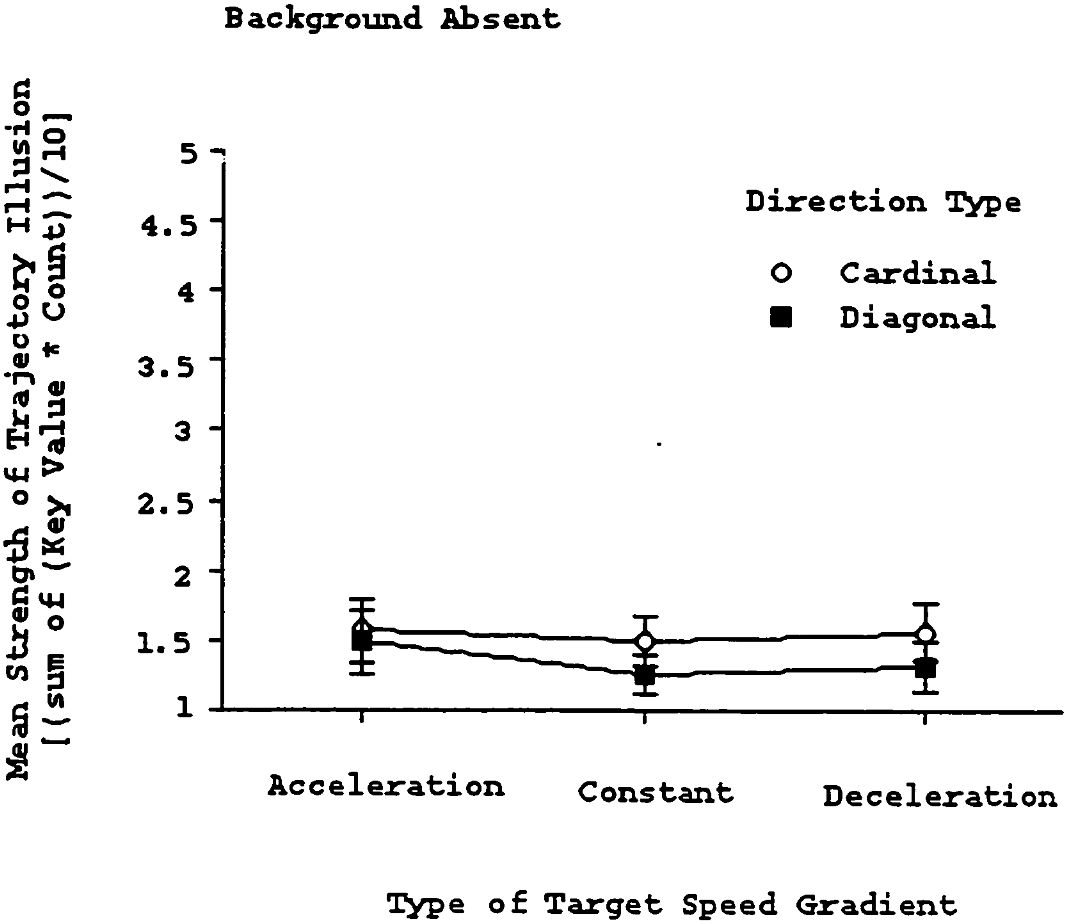


Figure 7. Nonsignificant interaction between Target Speed Gradient and Target Direction for Background Absent condition.

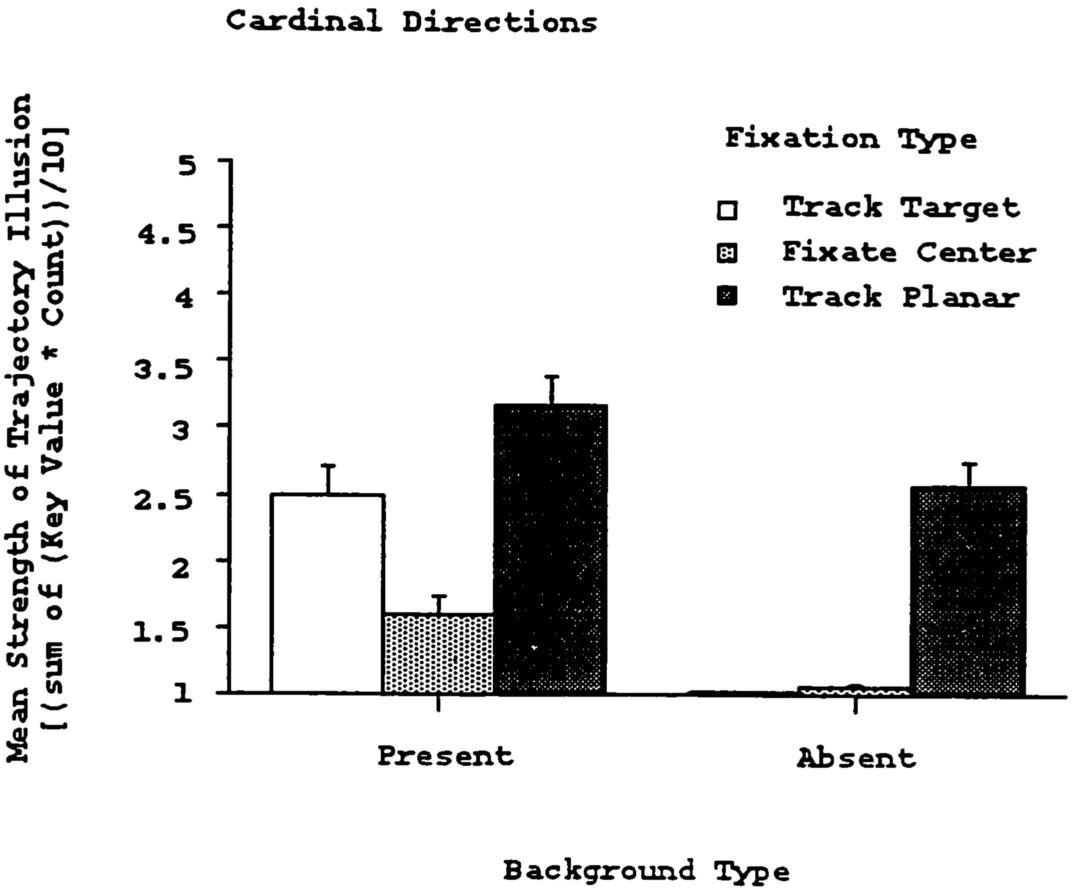


Figure 8. Statistically significant interaction between Background and Fixation for Cardinal Directions.

conditions was statistically significant when pursuing the target, F (2, 10) = 63.39, $p < 0.01$, and when pursuing the planar dot, F (2, 10) = 10.80, $p < 0.01$, but not when maintaining fixation on a stationary dot, F (2, 10) = 8.314, $p > 0.01$ (see Appendix B). Contrary to expectations was the finding that the strength of the trajectory illusion did not vary with the speed gradient of the target dot, F (2, 10) = 1.213, $p > 0.05$ (see Figures 9 and 10).

Results are also consistent with the hypothesis that eye movements play a role in the trajectory illusion. Specifically, the strength of the illusion was stronger when pursuing the target in the presence of background motion than when fixating on a stationary dot, Tukey HSD (3, 10) = 0.905, $p < 0.05$. Similarly, pursuit of a planar dot resulted in more illusory reports than when fixating on a stationary dot, Tukey HSD (3, 10) = 1.589, $p < 0.05$. Interestingly, the degree to which straight trajectories appeared curved was stronger when pursuing a planar dot than when pursuing the target dot, Tukey HSD (3, 10) = 0.684, $p < 0.05$.

Not predicted by either the induced motion or the SPEM hypothesis was the finding that pursuit of the planar dot in the absence of background motion resulted in stronger illusory reports than when pursuing a target, Tukey HSD

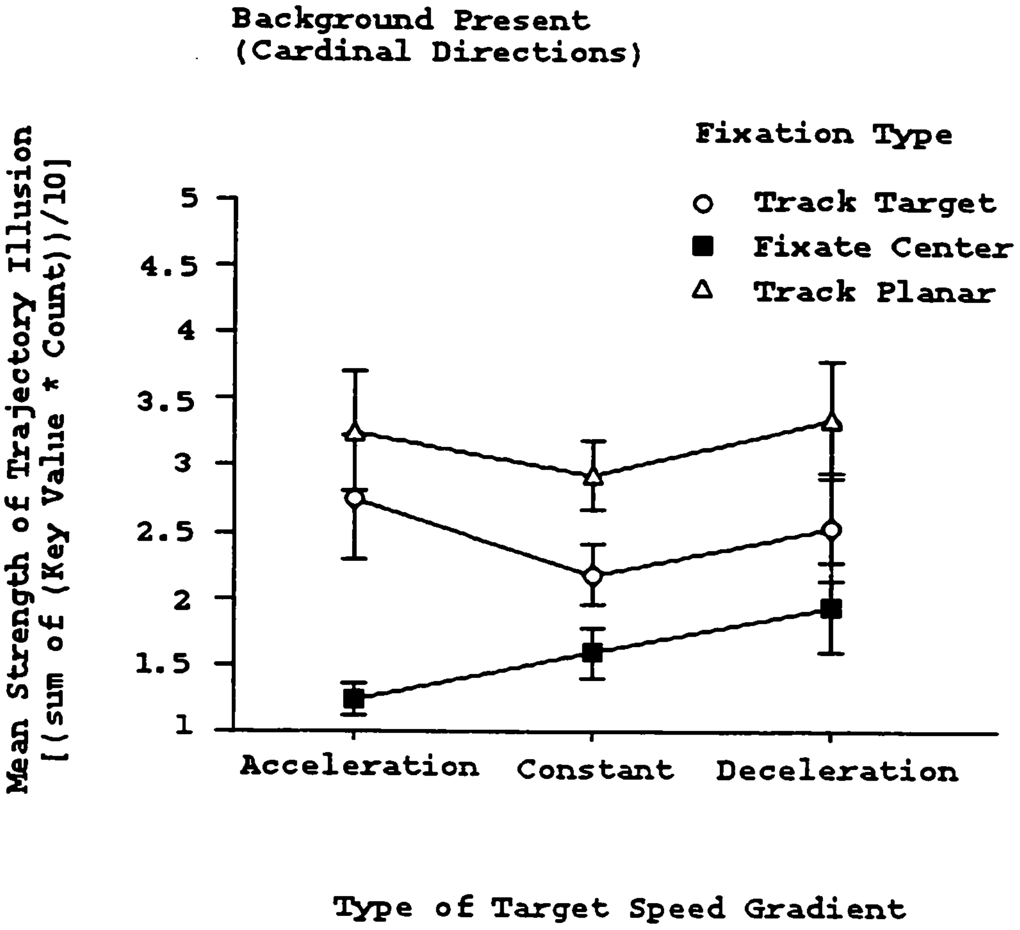


Figure 9. Nonsignificant interaction between Target Speed Gradient and Fixation for Background Present condition (Cardinal Directions).

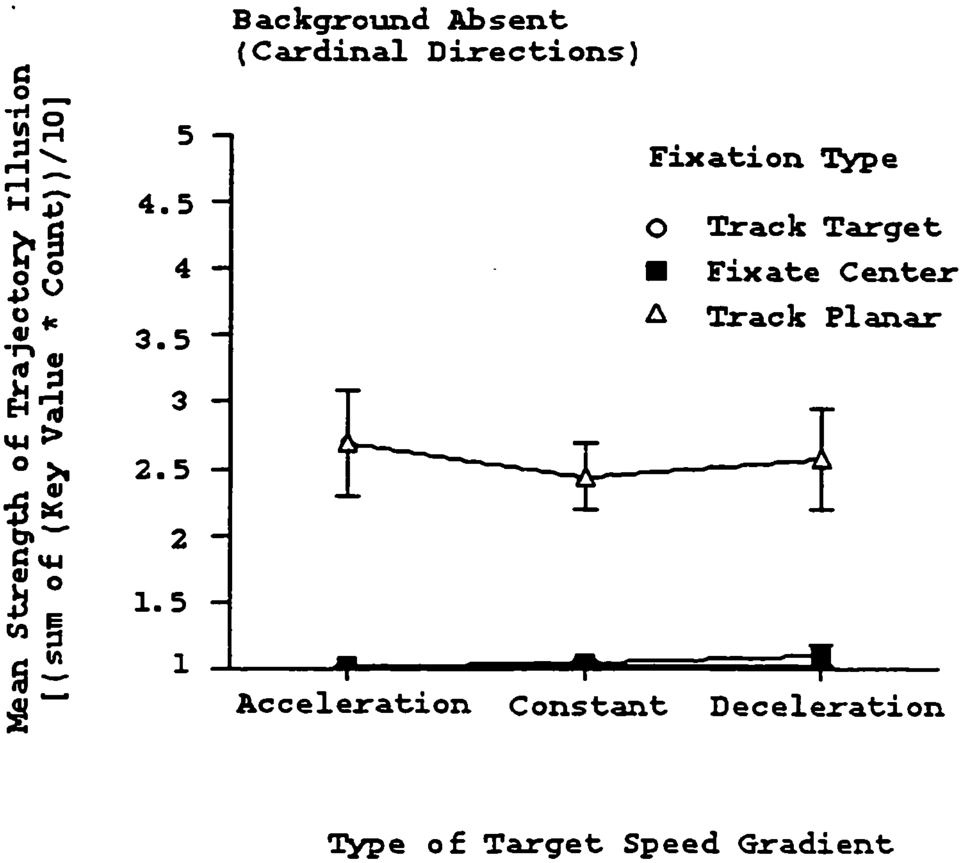


Figure 10. Nonsignificant interaction between Target Gradient and Fixation for Background Absent condition (Cardinal Directions).

(3, 10) = 1.553, $p < 0.05$, or when fixating on a stationary dot, Tukey HSD (3, 10) = 1.514, $p < 0.05$. In comparison, the latter two conditions, both indicating that straight trajectories were correctly identified as such, did not significantly differ from one another, Tukey HSD (3, 10) = 0.039, $p > 0.05$ (see Figure 8).

Diagonal directions (225 and 315 degrees). The interaction between type of background, type of target speed gradient, and type of fixation was statistically significant, F (4, 20) = 7.527, $p < 0.05$. Detailed analyses of the interaction, as in the analyses of the cardinal directions, are consistent with the idea that both induced motion and eye movements contribute to the perception of straight trajectories appearing curved (see Appendix C). Specifically, regardless of the type of speed gradient or the type of fixation, there was a decrease in the perceived strength of the illusion when the inducing, background motion was removed, F (1, 5) = 22.298, $p < 0.05$ (see Figure 11).

The pattern of results for the Background Present condition is also consistent with the speed-dependent induced motion hypothesis. When observers were asked to track the planar dot, the presence of the trajectory

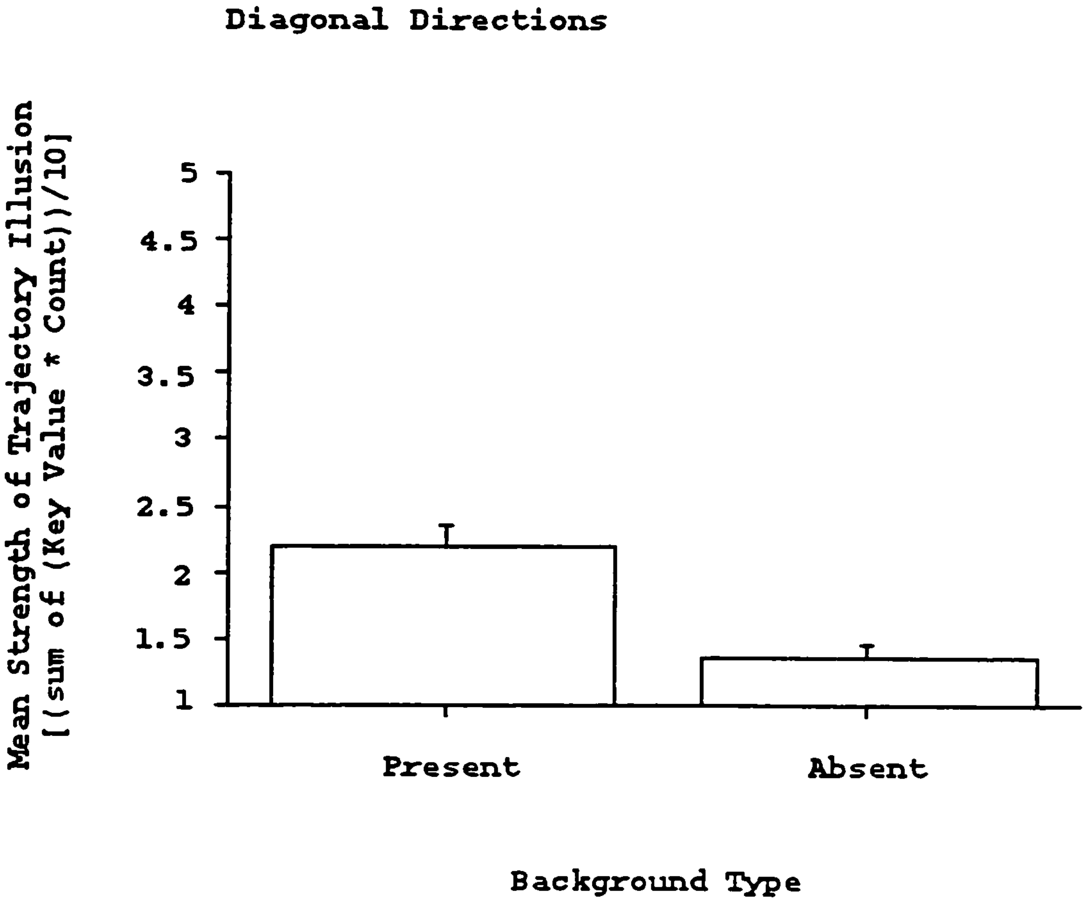


Figure 11. Statistically significant main effect of Background for Diagonal Directions.

illusion was more pronounced for target dots that accelerated than for those that moved with a constant speed, Tukey HSD (3, 20) = 1.05, $p < 0.05$. A similar pattern of results was found between decelerating and constant-velocity target dots, Tukey HSD (3, 20) = 0.675, $p < 0.05$. Also consistent with the speed-dependent induced motion hypothesis was the finding that the strength of the illusion did not differ when judging the trajectory of the accelerating versus decelerating target dot, Tukey HSD (3, 20) = 0.375, $p > 0.05$ (see Figure 12).

When asked to track the target dot in the Background Present condition, observers judged the strength of the trajectory illusion to be more pronounced for the accelerating than for the decelerating, Tukey HSD (3, 20) = 1.058, $p < 0.05$, or constant-velocity target dot, Tukey HSD (3, 20) = 1.508, $p < 0.05$. In contrast, when observers fixated on a stationary dot, they perceived the trajectory illusion to be stronger for the decelerating than for the accelerating, Tukey HSD (3, 20) = 1.341, $p < 0.05$, or constant-velocity target dot, Tukey HSD (3, 20) = 0.941, $p < 0.05$. Despite the different pattern of results for the Track Planar, Track Target, and Fixate Center conditions, the differences between the fixation types for decelerating and constant-velocity target dots were not statistically

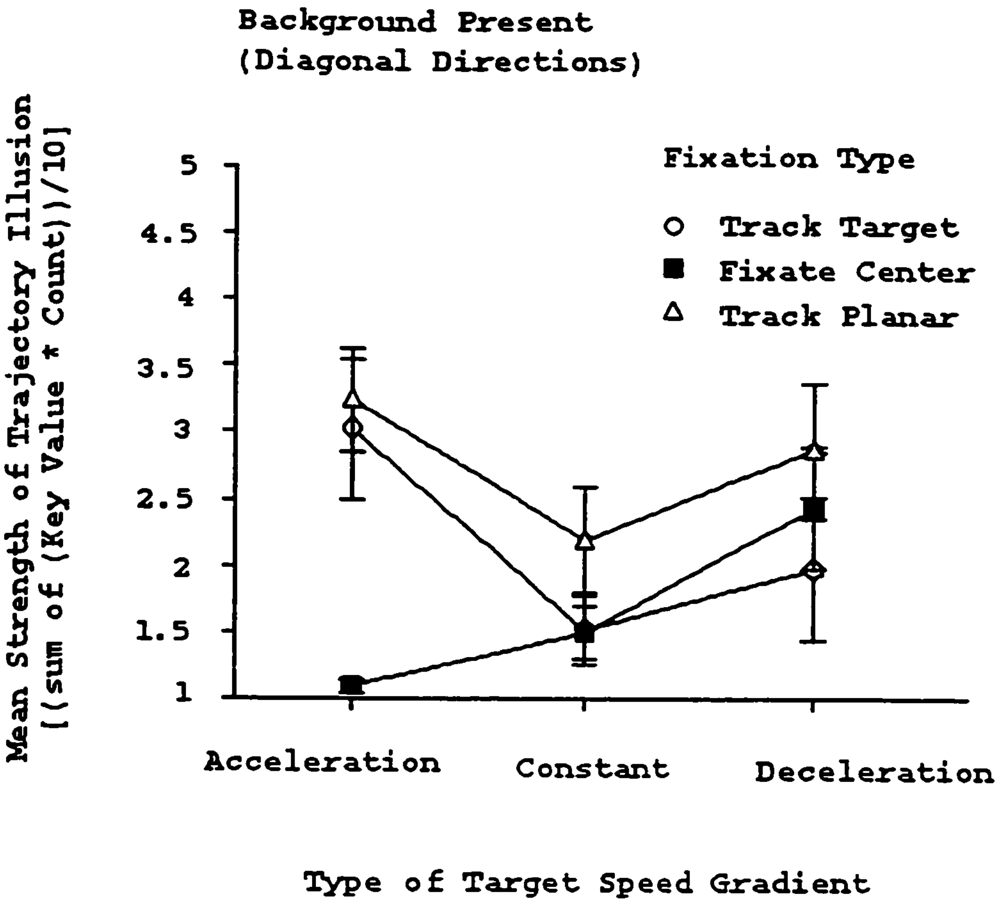


Figure 12. Statistically significant interaction between Target Speed Gradient and Fixation when background is present (Diagonal Directions).

significant, Fs (2, 20) = 7.997 and 6.225, respectively, ps > 0.00357 (see Figure 12).

For the accelerating target dots, however, there was a significant difference between the different types of fixation. Specifically, the strength of the trajectory illusion was stronger when pursuing the target than when fixating on a stationary dot, Tukey HSD (3, 20) = 1.933, $p < 0.05$. A similar pattern of results was found between the Track Planar and Fixate Center conditions, Tukey HSD (3, 20) = 2.15, $p < 0.05$. The difference between the amount of illusion perceived when tracking the planar versus when tracking the target dot, however, was not statistically different, Tukey HSD (3, 20) = 0.217, $p > 0.05$ (see Figure 12).

The differences that existed between the accelerating, decelerating, and constant-velocity speed gradients observed in the Background Present condition disappeared when tracking the planar dot in the absence of background motion, F (2, 20) = 4.41, $p > 0.00357$. Similarly, differences between the various speed gradients observed in the Background Present condition disappeared when tracking the target, F (2, 20) = 0.0196, $p > 0.00357$, and when fixating on a stationary dot, F (2, 20) = 0.0123, $p > 0.00357$ (see Figure 13).

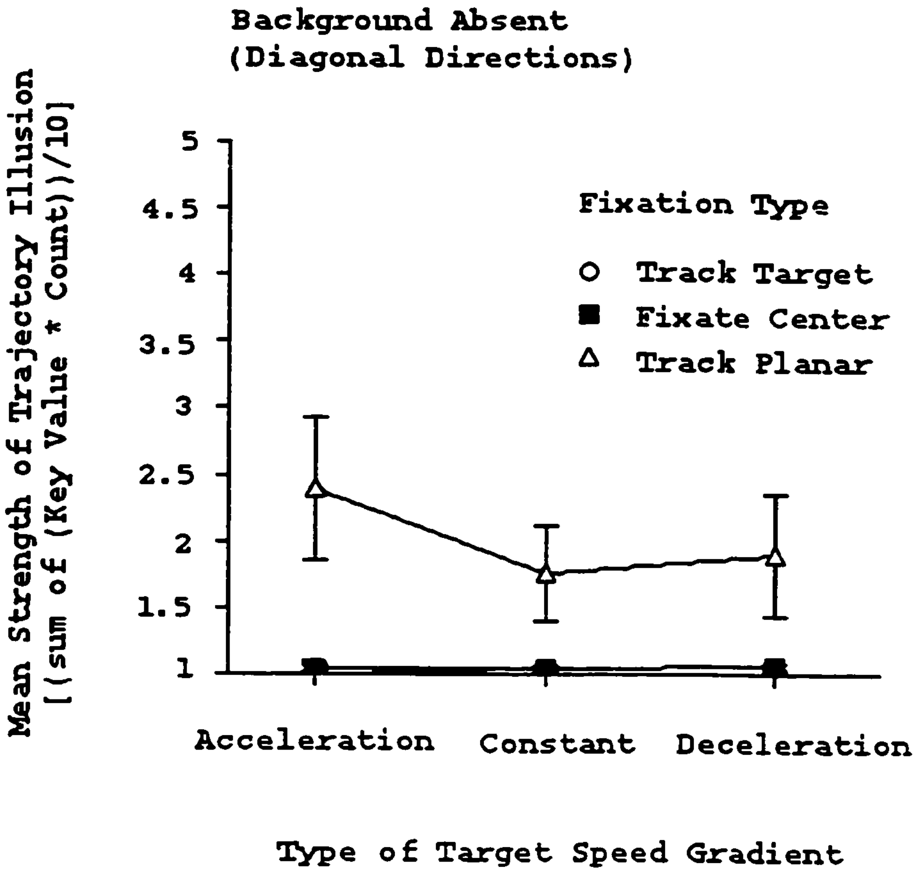


Figure 13. Statistically significant interaction between Target Speed Gradient and Fixation when background is absent (Diagonal Directions).

Interestingly, pursuing the planar dot in the absence of background motion resulted in more straight, accelerating target dots being perceived as curved compared to when pursuing the target, Tukey HSD (3, 20) = 1.35, $p < 0.05$, or when fixating on a stationary dot, Tukey HSD (3, 20) = 1.359, $p < 0.05$. Similarly, judging the trajectory of a decelerating target dot while pursuing the planar dot resulted in more illusory reports compared to when pursuing the target, Tukey HSD (3, 20) = 0.884, $p < 0.05$, or when fixating on a stationary dot, Tukey HSD (3, 20) = 0.825, $p < 0.05$ (see Figure 13). This pattern of results was not statistically significant for those target dots with a constant-velocity, F (2, 20) = 7.164, $p > 0.00357$. For the accelerating speed gradient, pursuit of the target dot and fixation on the stationary dot did not statistically differ from one another, Tukey HSD (2, 20) = 0.009, $p > 0.05$. Pursuit of the target dot and fixation on the stationary dot also did not significantly differ from one another for decelerating target dots, Tukey HSD (2, 20) = 0.059, $p > 0.05$ (see Figure 13).

Discussion

Findings from Experiment 1 are consistent with preliminary observations of the current investigation in that observers reported straight target trajectories as curved when tracking an accelerating, target dot. In addition, for both cardinal and diagonal directions, straight trajectories were perceived as curved significantly more often when the background was present than when it was absent, thereby suggesting that induced motion contributed to the trajectory illusion. Although the magnitude of their contribution varied with the direction of the target dot, eye movements also appeared to play a role in the trajectory illusion. Specifically, when the background was present, observers indicated seeing straight trajectories as more curved when pursuing the planar or the target dot than when fixating on a stationary dot -- though for diagonal directions, this pattern of results only applied to accelerating target dots.

Although not consistent across direction type, the speed gradient of the target dot did seem to affect the degree to which observers perceived illusory curved trajectories. Specifically, the trajectory illusion was reported more often for accelerating and decelerating target dots than for those that moved with a constant speed, that is, when the target dot moved diagonally from the center to the periphery.

Not predicted by either the induced motion or the SPEM hypothesis was the finding that the trajectory illusion generally occurred in the absence of background motion when tracking a planar dot, but not when tracking a target dot or when maintaining fixation on a stationary, central dot. According to the induced motion hypothesis, no illusion should have been reported in the Background Absent condition, and according to the SPEM hypothesis, tracking a target dot should also have elicited the trajectory illusion. In other words, the perception of straight trajectories as curved when tracking a planar dot in the absence of background motion may have occurred for a reason other than SPEMs.

Before entertaining this idea, however, the possibility that this finding may be due to there being two moving dots in the Track Planar condition, but only one moving dot in the Track Target and Fixate Center conditions needs to be examined (see Figure 14). In other words, the reason why tracking the planar dot in the Background 'Absent' condition resulted in more illusory reports may be due to there being a minimal background for this condition, but no background in the latter two conditions. Experiment

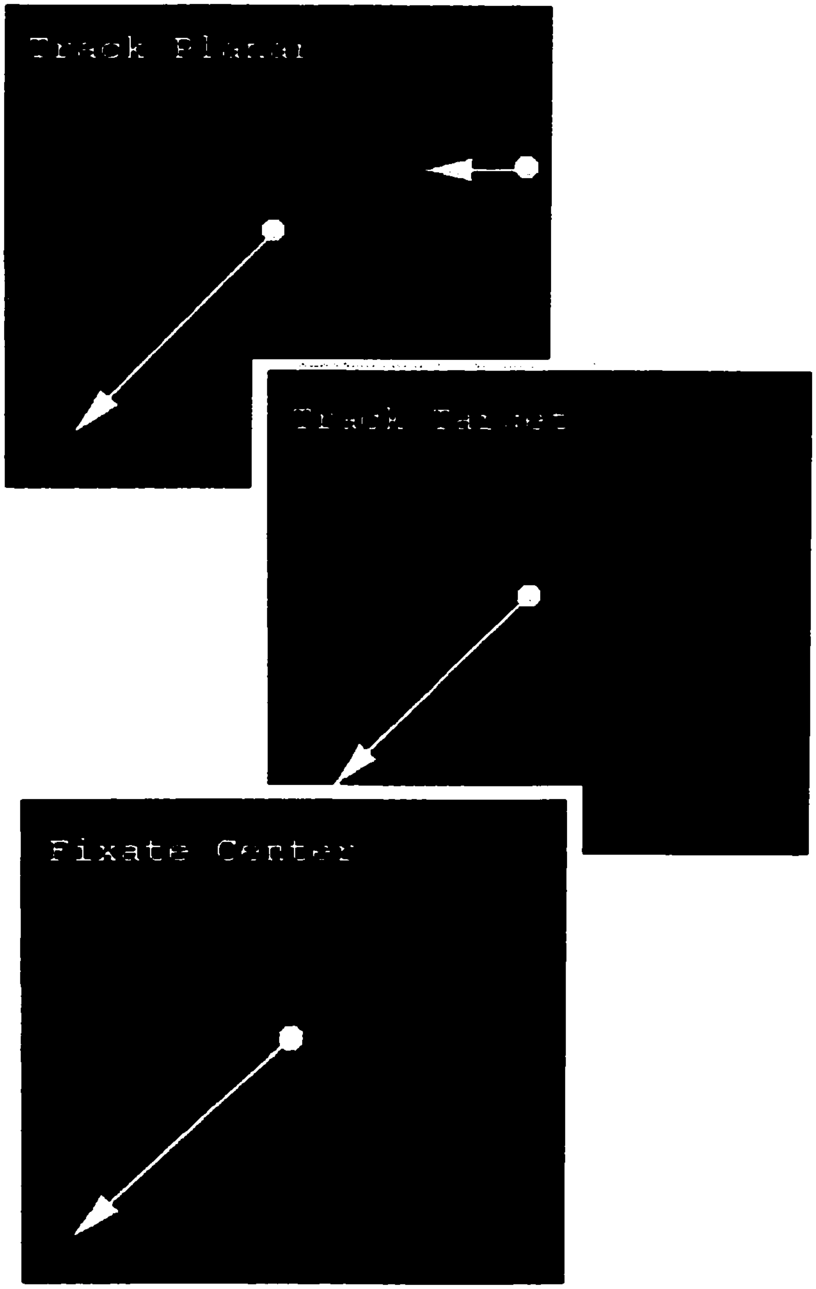


Figure 14. Minimal background hypothesis for Track Planar condition.

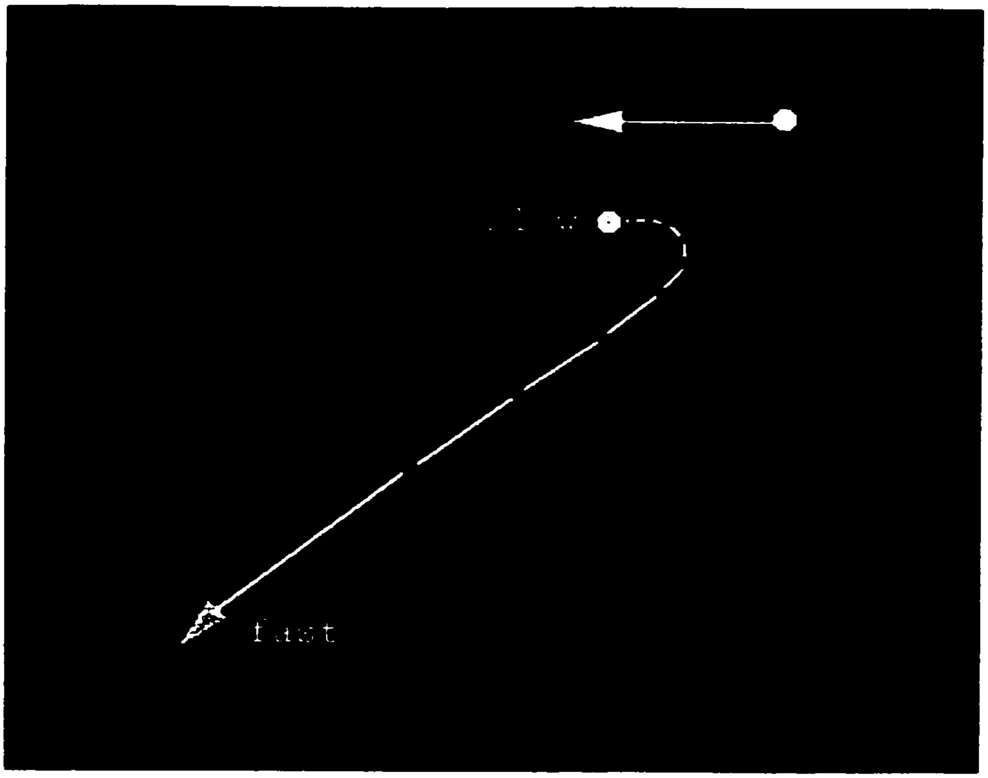
2 addresses the possibility that a single-dot background may be sufficient in eliciting straight trajectories to be perceived as curved.

Experiment 2

This experiment was designed to address the question of whether a single-dot background is sufficient to elicit the trajectory illusion. The Track Target condition and the Fixate Center conditions of Experiment 1 were repeated using a single-dot background. In other words, all conditions of the experiment contained two moving dots -- one of which was the target dot and the other was the single dot background.

Should the reason behind the trajectory illusion of the Background Absent, Track Planar condition of Experiment 1 be due to there being a minimal background present, then the straight target trajectories for the Track Target and Fixate Center conditions of Experiment 2 should also be perceived as curved. In other words, a single-dot background may be able to induce a straight target dot trajectory to appear curved. If a single dot is able to elicit the trajectory illusion, then the contribution of eye movements and the target speed gradient also needs to be examined.

Alternatively, the reason why the trajectory illusion exists when tracking a planar dot may be due to the fact that the straight target trajectories physically trace a curved trajectory on the retina. In other words, the amount by which the tracked, planar dot displaces the target dot is inversely related to the speed of the target dot (see Figure 15). This inverse relation between size of displacement and speed is analogous to that of the speed-dependent induced motion hypothesis.



<u>Figure 15</u>. Curved trace hypothesis for Track Planar condition.

Method

Participants

Five of the six psychophysical observers from Experiment 1 participated in all conditions of Experiment 2. Three of the five observers were naive to the purpose of the experiment, and of the five, one was male and four were female.

Procedure

For the Track Target and Fixate Center conditions of Experiment 1 in which the target dot was presented without a background, a single, leftward-moving, planar dot, identical to the one used in the Track Planar condition, was added. As in Experiment 1, observers pressed the spacebar to initiate the experiment. Upon the spacebar being pressed, a red fixation dot appeared in the center of the screen. Observers were asked to fixate on the central dot until it turned white, or were instructed to keep their eyes in the center of the screen without the aid of a fixation dot. As before, observers were required to make judgments about the trajectory of the target dot.

Results

As in Experiment 1, analyses of the data were split by target direction due to the slower-moving cardinal directions being more influenced by the single-dot background than the faster-moving diagonal directions, F (1, 4) = 8.471, $p < 0.05$ (see Appendix D). Similarly, degrees of freedom and alpha level were adjusted when the sphericity assumption was violated, and when multiple post-hoc analyses were performed.

Cardinal directions (0 and 180 degrees). Results are consistent with the hypothesis that the trajectory illusion experienced when pursuing the planar dot in the Background Absent condition of Experiment 1 is due to a curved trajectory being traced on the retina, and not due to induced motion. In other words, a single background dot was not sufficient to elicit the illusion for the Track Target condition compared to the Track Planar condition, Tukey HSD (3, 8) = 1.813, $p < 0.05$. A similar pattern of results was found for the Fixate Center condition in comparison to the Track Planar condition, Tukey HSD (3, 8) = 1.623, $p < 0.05$ (see Figure 16).

Diagonal directions (225 and 315 degrees). Despite the fact that the diagonal directions were faster than the

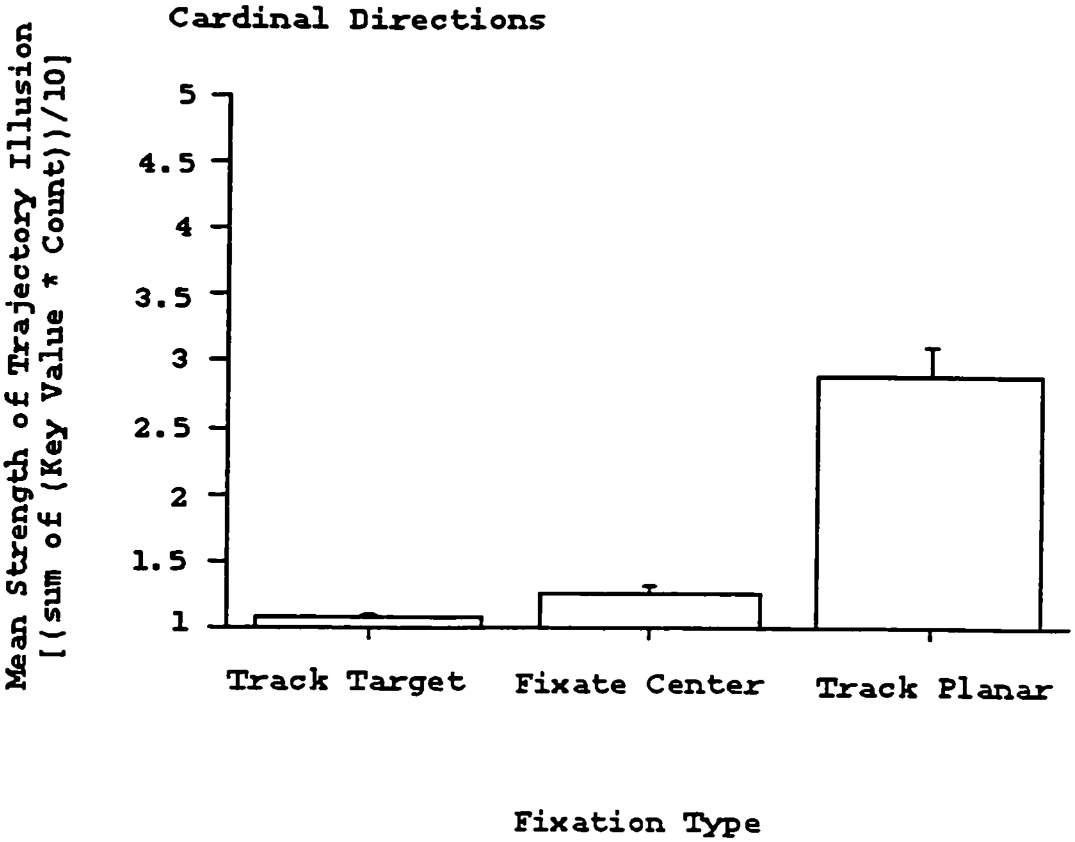


Figure 16. Statistically significant main effect of Fixation for Cardinal Directions.

cardinal directions, the same pattern of results was obtained. Specifically, compared to the Track Planar condition, asking observers to track a target dot or to fixate on a stationary, central dot in the presence of a single-dot background was not enough to elicit the trajectory illusion, Tukey HSDs (3, 8) = 1.733 and 1.64 respectively, $ps < 0.05$ (see Figure 17).

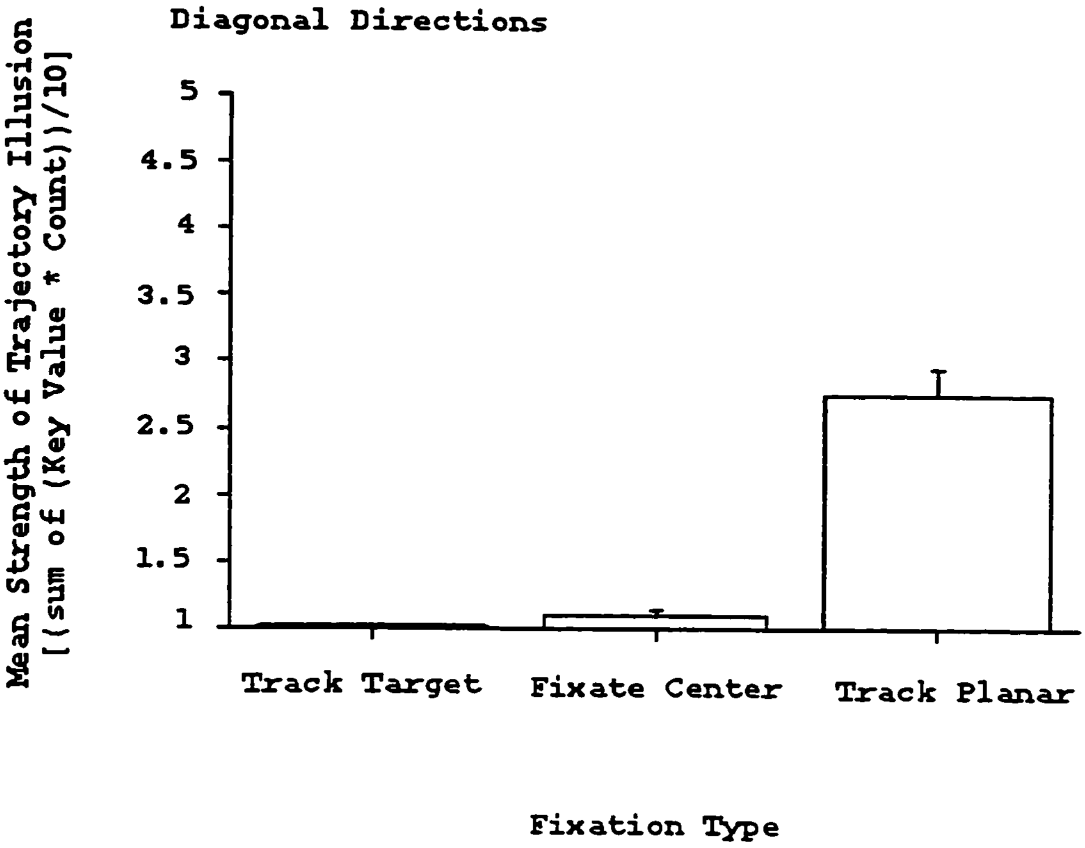


Figure 17. Statistically significant main effect of Fixation for Diagonal Directions.

Discussion

Findings from Experiment 2 are not consistent with the minimal background hypothesis in that judging the trajectory of the target dot in the presence of a single-dot background resulted in very little, if any, curved trajectories when tracking the target dot or while maintaining central fixation. However, results for both cardinal and diagonal directions are consistent with the idea that curved trajectories in the planar condition occur because the target dot physically traces a curved trajectory on the retina.

A question that arises is whether this pattern of results also occurs when tracking the target dot, but judging the trajectory of the planar dot. In other words, will the straight trajectory of the planar dot appear curved when tracking straight or curved target trajectories? Experiment 3 examines the possibility that a target dot may influence the degree to which a planar dot is perceived as curved.

Experiment 3

This experiment examines the degree to which a target dot influences the trajectory of a planar dot just as a planar dot altered the perceived trajectory of a target dot in Experiments 1 and 2. Although the same 2-dot stimulus from Experiment 2 was used in the present experiment, the instructions to observers were different. Specifically, observers were asked to track the target dot, but make judgments about the trajectory of the planar dot.

A finding that the straight trajectories of the planar dots were perceived as curved would indicate that the frame of reference -- the point of attentional focus -- is more important than the stimulus properties. In contrast, a finding that the straight trajectories of the planar dots were perceived as such would indicate that there is something unique about horizontal motion that alters the perception of all other objects in visual space.

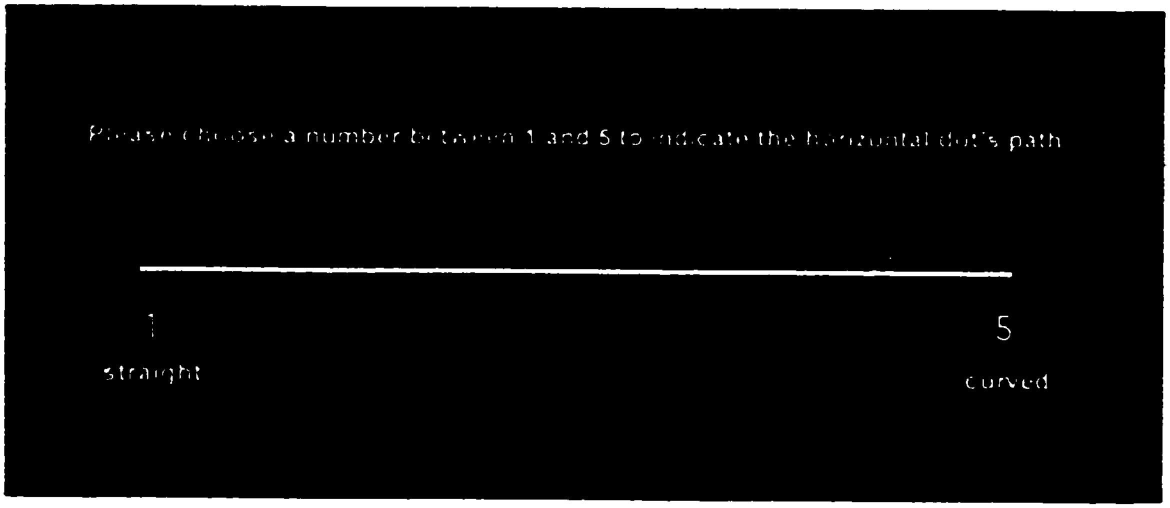
Method

Participants

The same five observers who participated in Experiment 2 also participated in Experiment 3.

Procedure

Upon pressing the spacebar to initiate the experiment, observers fixated on a central red dot until it turned white. Though they were presented with the same stimulus as in Experiment 2, observers were asked to judge the trajectory of the planar dot while tracking the target dot rather than vice versa. At the end of the stimulus presentation, observers were asked to rate the degree to which the planar dot appeared curved (see Figure 18). As before, a value of 1 corresponded to no curvature perceived, and a value of 5 corresponded to a large degree of curvature perceived.



Please choose a number between 1 and 5 to indicate the horizontal dot's path

<u>Figure 18</u>. Example of response options provided to observers when asked to track the target, but judge the trajectory of the planar dot.

Results

Analyses of the data were not split by target direction due to the influence of the slower-moving cardinal directions on the single-dot background not being statistically different from that of the faster-moving diagonal directions, F (1, 4) = 6.994, $p > 0.05$ (see Appendix E). As in Experiments 1 and 2, degrees of freedom and alpha level were adjusted when the sphericity assumption was violated, and when multiple post-hoc analyses were performed.

Results from Experiment 2 suggested that tracking a planar dot, presented with a single-dot or many-dots background, elicited a trajectory illusion because the target dot physically traced a curved trajectory on the retina. However, findings from Experiment 3 are not consistent with the curved-trace hypothesis, for when observers were asked to track the target, but judge the trajectory of the planar dot, they reported seeing no or little illusion, that is, compared to the track-planar-judge-target condition, F (1, 4) = 11.348, $p < 0.05$ (see Figure 19).

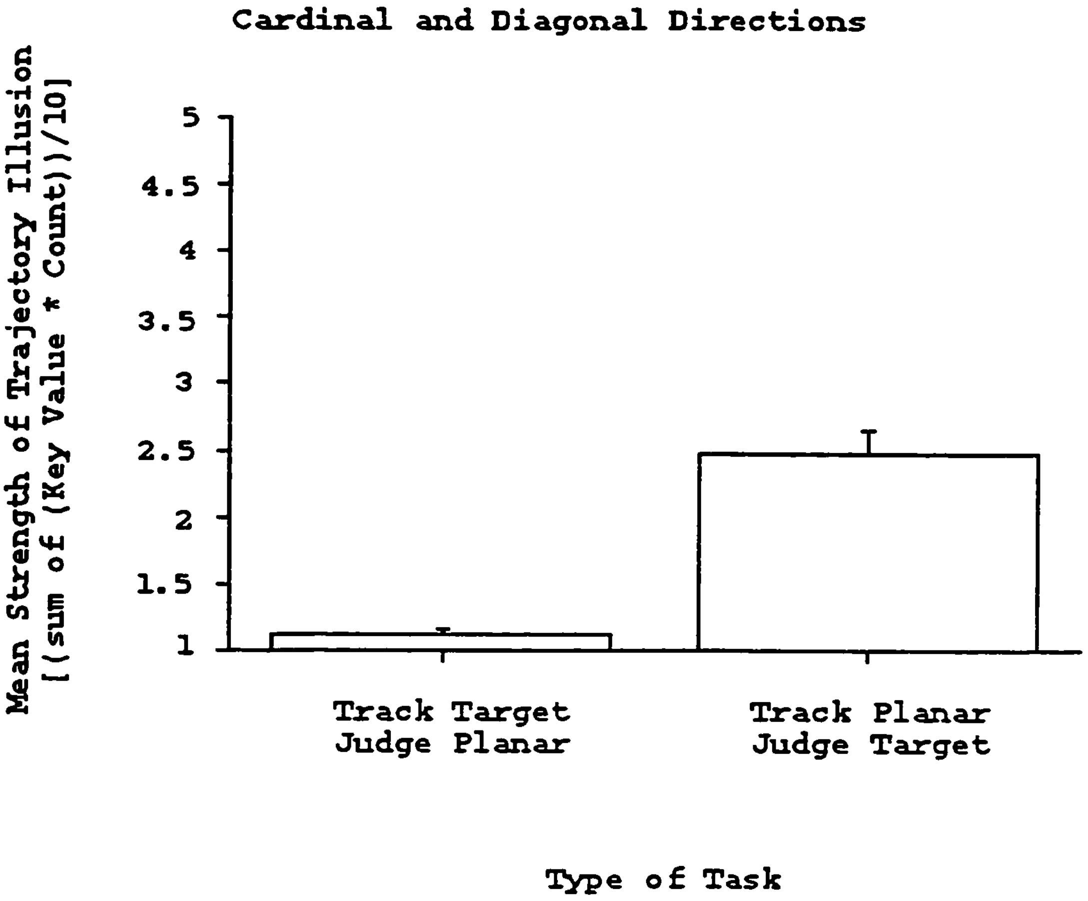


Figure 19. Statistically significant main effect of Task across Direction Type.

Discussion

Findings from Experiment 3 are not consistent with the curved-trace hypothesis in that the track-planar-judge-target condition resulted in significantly more illusory trajectories being perceived than in the track-target-judge-planar condition. The suggestion is that the brain may process horizontal motion differently from other directions of motion.

General Discussion

Overall, induced motion contributes to the trajectory illusion in that straight target trajectories were perceived as curved when presented with background planar motion, but were seen veridically in its absence. In addition, smooth pursuit eye movements (SPEMs) influence the strength of the illusion in that, when the background was present, pursuit of a target dot and of a planar dot, in comparison to stationary fixation, resulted in an increase in the strength of the illusion across all speed gradients for the cardinal directions, but only for the accelerating condition of the diagonal directions.

In contrast, the influence of the target speed gradient on the strength of the trajectory illusion remains inconclusive due to the confound between target direction and average target speed. In other words, the reason why the target speed gradient did not appear to influence the strength of the trajectory illusion for the cardinal directions, but did so for the diagonal directions can be attributed to the enhancing or masking effect of induced motion on the slower- or faster-moving, constant-velocity target dots, respectively (see Figure 6). Similarly, any conclusion about the contribution of SPEMs on the strength of the trajectory illusion across directions is also affected by the average velocity confound, and, therefore, needs to be interpreted with caution.

Not predicted by the induced motion or the SPEM hypothesis was the finding that tracking the planar dot in the absence of background motion also resulted in the perception of straight target trajectories as curved. Due to there being two moving dots present when tracking the planar dot, but only one moving dot when tracking the target dot or when fixating on a stationary dot in the Background Absent condition, this result was thought to be due to there being a minimal background present in the former, but not in the latter two conditions (minimal background hypothesis). Yet, results from Experiment 2 suggest that the reason why straight target trajectories appeared curved when tracking a planar dot was not due there being a minimal background present, but due to a curved trajectory being physically traced on the retina (curved trace hypothesis).

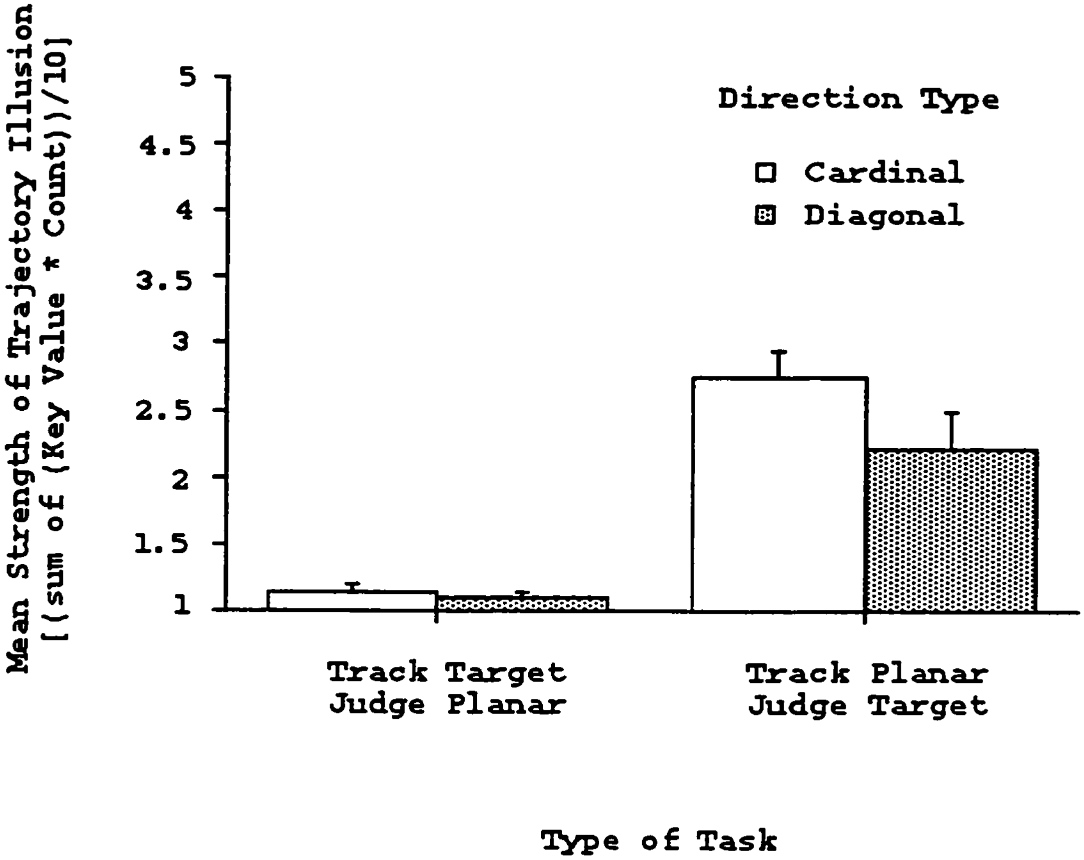
Results from Experiment 3, however, suggest that the curved trace hypothesis may not be sufficient in explaining the trajectory illusion, for judging the trajectory of the planar dot while tracking the radial, target dot did not result in straight planar trajectories being perceived as curved. One hypothesis is that the brain processes horizontal motion differently from other directions of motion. From an evolutionary standpoint, the findings from Experiment 3 are consistent with the fact that horizontally moving objects in the real world are rarely perceived as curving when a second object is tracked, thereby suggesting that the brain may interpret horizontal motion as reflecting a stable feature in the natural environment (Gibson, 1954).

Alternatively, these findings may be attributed to context effects in that observers may have used the edge of the stimulus display or of the screen as a guide for judging the trajectory of the planar dot; whereas, at least for diagonal directions, no direct comparison could have been made when reporting the trajectory of the target dot. Had there been no average velocity confound, results from the cardinal compared to the diagonal directions would have provided some insight as to whether observers' judgments were based on contextual cues. In other words, if the average target speeds were the same across direction type, then the cardinal directions may have resulted in no or very little illusion. However, due to the fact that, even with this confound, judging the trajectory of a cardinally-moving target dot resulted in more illusory reports than judging the trajectory of the planar dot, findings from

Experiment 3 appear to favour the horizontal motion rather than the context effect hypothesis (see Figure 20).

The implication of the horizontal motion hypothesis is that the reason behind perceiving straight trajectories as curved when pursuing the planar dot may not be due to SPEMs per say, but possibly due to the brain interpreting the planar motion as a stable characteristic of the environment. In other words, just as SPEMs affect the perception of target and background object motion (Mack & Herman, 1972, 1973, 1978), the contribution of SPEMs to the trajectory illusion is twofold. Under one set of circumstances such as when tracking an accelerating target dot in the presence of background motion, SPEMs, themselves, can elicit the perception of straight trajectories as curved. Under another set of circumstances such as when tracking a planar dot in the absence of background motion, SPEMs can elicit the path of other objects to appear curved when, in fact, it is straight.

The finding that the trajectory illusion is due to both induced motion and SPEMs is not only consistent with previous neurophysiological findings proposing that there is a link between the two systems, but it is also consistent with psychophysical findings suggesting that SPEMs increase the extent to which induced motion is



<u>Figure 20</u>. Statistically significant main effect of Task for Cardinal and Diagonal Directions.

effective (Wurtz, Yamasaki, Duffy, & Roy, 1990; Becklen & Wallach, 1985).

In contrast, at least for the case of accelerating target dots, results of the current investigation question the existence of an eye movement compensation mechanism due to there being uncertainty as to whether observers maintained stationary fixation. Specifically, due to the fact that the fixation target was presented before the onset of the motion display, the horizontal, but not the vertical component of eye movements was measured, and that observers' eyes were allowed to deviate 4 degrees from the center (Duffy & Wurtz, 1993), the possibility that the trajectory illusion, as a result of SPEMs, contributes to the illusory FOE shift is still plausible. In other words, had observers maintained stationary fixation when judging the location of the FOE, then the possibility of the trajectory illusion playing a role in the illusory FOE shift disappears.

Related to the idea that the trajectory illusion contributes to the illusory FOE shift is whether the trajectories of SPEMs coincide with those reported perceptually. This question is interesting in that, regardless of the outcome, results would provide direct, behavioural evidence as to whether the motion and the SPEM systems are linked.

However, prior to examining the questions as to whether the trajectory illusion contributes to the illusory FOE shift, and whether the paths of SPEMs coincide with those reported perceptually, future experiments need to determine the role of the target speed gradient on the trajectory illusion, itself, by holding constant the distance over which target dots travelled. In addition, future experiments should maintain the same number of dots across all conditions, should provide observers with a more neutral measure of the degree of curvature perceived, and should eliminate all context effects in order to improve upon the design flaws encountered in this investigation.

In sum, the current investigation, by examining the underpinnings of the trajectory illusion, has provided some insight as to the importance of the brain to retrieve information about self-motion from multiple sources in order to navigate safely in the environment, for depending on visual and oculomotor information alone leaves observers wondering whether the paths they choose are straight or curved.

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Appendix A

Summary Tables for Cardinal vs. Diagonal Directions

(Experiment 1)

Table 1

Analysis of Variance Summary Table for Cardinal Versus Diagonal Directions When Background is Present (Experiment 1)

Source	df	SS	MS	F
Within-Subjects				
Fixation (A)[a]	2	32.424	16.212	16.788***
Error	10	9.657	.966	
Direction (B)[b]	1	1.278	1.278	8.179*
Error	5	.782	.156	
Speed Gradient (C)[c]	2	5.878	2.939	3.138
Error	10	9.367	.937	
A x B[d]	2	1.256	.628	3.214
Error	10	1.954	.195	
A x C[e]	4	10.235	2.559	6.816**
Error	20	7.508	.375	
B x C[f]	2	1.309	.655	5.549*
Error	10	1.180	.118	
A x B x C[g]	4	1.871	.468	5.154**
Error	20	1.815	.091	

Note. Due to the possibility of the sphericity assumption being violated, all F values were compared against critical values adjusted by the Huynh-Feldt epsilon.

[a]H-F Epsilon = 1.284. [b]1.000. [c]1.656. [d].780. [e]1.088. [f].716. [g].938.

$^{*}p < 0.05$. $^{**}p < 0.01$. $^{***}p < 0.001$.

Table 2

Simple Main Effect ANOVA Summary Table for Direction (B) X Speed Gradient (C) Interaction (Experiment 1)

Source	df	SS	MS	F
Within-Subjects				
B at Acceleration [a]	1	.010	.010	.088
B at Constant [a]	1	2.278	2.278	19.297*
B at Deceleration [a]	1	.305	.305	2.58
Error	10	1.180	.118	

Note. Due to the possibility of the sphericity assumption being violated, all F values were compared against critical values adjusted by the Huynh-Feldt epsilon. In addition, alpha levels were adjusted according to the Bonferroni correction factor.

[a] H-F Epsilon = .716.

*$p < 0.0167$.

Table 3

Analysis of Variance Summary Table for Cardinal Versus Diagonal Directions When Background is Absent (Experiment 1)

Source	df	SS	MS	F
Within-Subjects				
Fixation (A)[a]	2	37.981	18.991	12.618*
Error	10	15.051	1.505	
Direction (B)[b]	1	.926	.926	9.509*
Error	5	.487	.097	
Speed Gradient (C)[c]	2	.387	.193	1.277
Error	10	1.515	.151	
A x B[d]	2	1.824	.912	9.060*
Error	10	1.007	.101	
A x C[e]	4	.877	.219	1.207
Error	20	3.635	.182	
B x C[f]	2	.148	.074	2.795
Error	10	.265	.026	
A x B x C[g]	4	.153	.038	2.828
Error	20	.270	.014	

Note. Due to the possibility of the sphericity assumption being violated, all F values were compared against critical values adjusted by the Huynh-Feldt epsilon.

[a]H-F Epsilon = .503. [b]1.000. [c].730. [d].563. [e].403. [f].678. [g].336.

$^{*}p < 0.05$. $^{**}p < 0.01$. $^{***}p < 0.001$.

Appendix B

Summary Tables for Cardinal Directions (Experiment 1)

Table 1

Analysis of Variance Summary Table for Cardinal Directions (Experiment 1)

Source	df	SS	MS	F
Within-Subjects				
Fixation (A)[a]	2	46.136	23.068	28.607**
Error	10	8.064	.806	
Background (B)[b]	1	20.716	20.716	23.751**
Error	5	4.361	.872	
Speed Gradient (C)[c]	2	.853	.426	1.213
Error	10	3.516	.352	
A x B [d]	2	4.961	2.480	7.970**
Error	10	3.112	.311	
A x C [e]	4	1.151	.288	1.586
Error	20	3.629	.181	
B x C [f]	2	.429	.215	1.371
Error	10	1.565	.156	
A x B x C [g]	4	.791	.198	2.935
Error	20	1.348	.067	

Note. Due to the possibility of the sphericity assumption being violated, all F values were compared against critical values adjusted by the Huynh-Feldt epsilon.

[a]H-F Epsilon = .538. [b]1.000. [c].822. [d]1.052. [e].514. [f]1.374. [g].669.

*$p < 0.05$. **$p < 0.01$. ***$p < 0.001$.

Table 2

Simple Main Effect ANOVA Summary Table for Fixation (A) X Background (B) Interaction (Experiment 1)

Source	df	SS	MS	F
Within-Subjects				
B at Track Target [a]	1	19.714	19.714	63.388*
B at Fixate Center [a]	1	2.586	2.586	8.314
B at Track Planar [a]	1	3.360	3.360	10.804*
Error	10	3.112	.311	

Note. Due to the possibility of the sphericity assumption being violated, all F values were compared against critical values adjusted by the Huynh-Feldt epsilon. In addition, alpha levels were adjusted according to the Bonferroni correction factor.

[a] df adjustment not necessary because H-F Epsilon = 1.052.

*$p < 0.01$.

Table 3

Simple Main Effect ANOVA Summary Table for Fixation (A) X Background (B) Interaction (Experiment 1)

Source	df	SS	MS	F
Within-Subjects				
A at Bkgd Present[a]	2	22.871	11.435	36.770*
A at Bkgd Absent[a]	2	28.233	14.117	45.390*
Error	10	3.112	.311	

Note. Due to the possibility of the sphericity assumption being violated, all F values were compared against critical values adjusted by the Huynh-Feldt epsilon. In addition, alpha levels were adjusted according to the Bonferroni correction factor.

[a] df adjustment not necessary because H-F Epsilon = 1.052.

$^*p < 0.01$.

Table 4

Tukey's HSD Multiple Comparison Summary Table for Fixation Type in Background Present Condition (Experiment 1)

Comparison	Mean Difference
Track Target vs. Fixate Center	.905*
Track Planar vs. Fixate Center	1.589*
Track Planar vs. Track Target	.684*

*$p < 0.05$.

Table 5

Tukey's HSD Multiple Comparison Summary Table for Fixation Type in Background Absent Condition (Experiment 1)

Comparison	Mean Difference
Fixate Center vs. Track Target	.039
Track Planar vs. Track Target	1.553*
Track Planar vs. Fixate Center	1.514*

*$p < 0.05$.

Appendix C

Summary Tables for Diagonal Directions (Experiment 1)

Table 1

Analysis of Variance Summary Table for Diagonal Directions (Experiment 1)

Source	df	SS	MS	F
Within-Subjects				
Fixation (A)[a]	2	21.025	10.512	10.647**
Error	10	9.873	.987	
Background (B)[b]	1	19.211	19.211	22.298**
Error	5	4.308	.862	
Speed Gradient (C)[c]	2	4.439	2.220	5.389*
Error	10	4.119	.412	
A x B[d]	2	1.365	.682	1.031
Error	10	6.619	.662	
A x C[e]	4	6.609	1.652	6.347**
Error	20	5.206	.260	
B x C[f]	2	2.001	1.000	3.200
Error	10	3.126	.313	
A x B x C[g]	4	4.584	1.146	7.527***
Error	20	3.045	.152	

Note. Due to the possibility of the sphericity assumption being violated, all F values were compared against critical values adjusted by the Huynh-Feldt epsilon.

[a]H-F Epsilon = .949. [b]1.000. [c]1.265. [d]1.009. [e].849. [f].874. [g]1.368.

$*p < 0.05$. $**p < 0.01$. $***p < 0.001$.

Table 2

Simple Interaction Effect ANOVA Summary Table for Fixation (A) X Speed Gradient (C) Interaction When Background Is Present (Experiment 1)

Source	df	SS	MS	F
Within-Subjects				
Fixation (A) x Speed Gradient (C)[a]	4	27.092	6.773	44.56*
A at Acceleration [a]	2	16.812	8.406	55.303*
A at Constant [a]	2	1.893	.946	6.225
A at Deceleration [a]	2	2.431	1.216	7.997
Error	20	3.045	.152	

Note. Due to the possibility of the sphericity assumption being violated, all F values were compared against critical values adjusted by the Huynh-Feldt epsilon. In addition, alpha levels were adjusted according to the Bonferroni correction factor.

[a] df adjustment not necessary because H-F Epsilon = 1.368.

*$p < 0.00357$.

Table 3

Tukey's HSD Multiple Comparison Summary Table for Fixation Type When Accelerating Speed Gradient & Background Are Present (Experiment 1)

Comparison	Mean Difference
Track Target vs. Fixate Center	1.933*
Track Planar vs. Fixate Center	2.15*
Track Planar vs. Track Target	.217

*$p < 0.05$.

Table 4

Simple Interaction Effect ANOVA Summary Table for Fixation (A) X Speed Gradient (C) Interaction When Background Is Present (Experiment 1)

Source	df	SS	MS	F
Within-Subjects				
Fixation (A) x Speed Gradient (C)[a]	4	27.092	6.773	44.56*
C at Track Target[a]	2	7.192	3.596	23.657*
C at Fixate Center[a]	2	5.688	2.844	18.71*
C at Track Planar[a]	2	3.398	1.699	11.176*
Error	20	3.045	.152	

Note. Due to the possibility of the sphericity assumption being violated, all F values were compared against critical values adjusted by the Huynh-Feldt epsilon. In addition, alpha levels were adjusted according to the Bonferroni correction factor.

[a] df adjustment not necessary because H-F Epsilon = 1.368.

*$p < 0.00357$.

Table 5

Tukey's HSD Multiple Comparison Summary Table for Fixation Type in Track Target & Background Present Condition (Experiment 1)

Comparison	Mean Difference
Deceleration vs. Constant	.45
Acceleration vs. Constant	1.508*
Acceleration vs. Deceleration	1.058*

*$p < 0.05$.

Table 6

Tukey's HSD Multiple Comparison Summary Table for Fixation Type in Fixate Center & Background Present Condition (Experiment 1)

Comparison	Mean Difference
Constant vs. Acceleration	.40
Deceleration vs. Acceleration	1.341*
Deceleration vs. Constant	.941*

*$p < 0.05$.

Table 7

Tukey's HSD Multiple Comparison Summary Table for Fixation Type in Track Planar & Background Present Condition (Experiment 1)

Comparison	Mean Difference
Deceleration vs. Constant	.675*
Acceleration vs. Constant	1.050*
Acceleration vs. Deceleration	.375

*$p < 0.05$.

Table 8

Simple Interaction Effect ANOVA Summary Table for Fixation (A) X Speed Gradient (C) Interaction When Background Is Absent (Experiment 1)

Source	df	SS	MS	F
Within-Subjects				
Fixation (A) x Speed Gradient (C)[a]	4	12.930	3.232	21.270*
A at Acceleration [a]	2	7.339	3.669	24.14*
A at Constant [a]	2	2.178	1.089	7.164
A at Deceleration [a]	2	2.931	1.466	9.642*
Error	20	3.045	.152	

Note. Due to the possibility of the sphericity assumption being violated, all F values were compared against critical values adjusted by the Huynh-Feldt epsilon. In addition, alpha levels were adjusted according to the Bonferroni correction factor.

[a] df adjustment not necessary because H-F Epsilon = 1.368.

*$p < 0.00357$.

Table 9

Tukey's HSD Multiple Comparison Summary Table for Fixation Type With Accelerating Speed Gradient & Background Absent (Experiment 1)

Comparison	Mean Difference
Track Target vs. Fixate Center	.009
Track Planar vs. Fixate Center	1.359*
Track Planar vs. Track Target	1.35*

*$p < 0.05$.

Table 10

Tukey's HSD Multiple Comparison Summary Table for Fixation Type With Decelerating Speed Gradient & Background Absent (Experiment 1)

Comparison	Mean Difference
Track Target vs. Fixate Center	.059
Track Planar vs. Fixate Center	.884*
Track Planar vs. Track Target	.825*

*$p < 0.05$.

Table 11

Simple Interaction Effect ANOVA Summary Table for Fixation (A) X Speed Gradient (C) Interaction When Background Is Absent (Experiment 1)

Source	df	SS	MS	F
Within-Subjects				
Fixation (A) x Speed Gradient (C)[a]	4	12.930	3.232	21.270*
C at Track Target [a]	2	.006	.002	.020
C at Fixate Center [a]	2	.004	.001	.012
C at Track Planar [a]	2	1.340	.670	4.407
Error	20	3.045	.152	

Note. Due to the possibility of the sphericity assumption being violated, all F values were compared against critical values adjusted by the Huynh-Feldt epsilon. In addition, alpha levels were adjusted according to the Bonferroni correction factor.

[a] df adjustment not necessary because H-F Epsilon = 1.368.

*$p < 0.00357$.

Appendix D

Summary Tables for Experiment 2

Table 1

Analysis of Variance Summary Table for Cardinal Versus Diagonal Directions (Experiment 2)

Source	df	SS	MS	F
Within-Subjects				
Direction (A) [a]	1	.318	.318	8.471*
Error	4	.150	.038	
Fixation (B)[b]	2	58.271	29.136	29.380**
Error	8	7.934	.992	
Speed Gradient (C)[c]	2	.730	.365	1.584
Error	8	1.845	.231	
A x B [d]	2	.040	.020	.741
Error	8	.216	.027	
A x C [e]	2	.042	.021	1.362
Error	8	.124	.015	
B x C [f]	4	1.080	.270	.899
Error	16	4.802	.300	
A x B x C [g]	4	.296	.074	2.554
Error	16	.463	.029	

Note. Due to the possibility of the sphericity assumption being violated, all F values were compared against critical values adjusted by the Huynh-Feldt epsilon.

[a]H-F Epsilon = 1.000. [b].504. [c].820. [d].572. [e]1.458. [f].429. [g].480.

*$p < 0.05$. **$p < 0.01$. ***$p < 0.001$.

Table 2

Analysis of Variance Summary Table for Cardinal Directions (Experiment 2)

Source	df	SS	MS	F
Within-Subjects				
Fixation (A)[a]	2	29.797	14.899	28.554**
Error	8	4.174	.522	
Speed Gradient (B)[b]	2	.534	.267	1.800
Error	8	1.186	.148	
A x B [c]	4	1.207	.302	1.364
Error	16	3.538	.221	

Note. Due to the possibility of the sphericity assumption being violated, all F values were compared against critical values adjusted by the Huynh-Feldt epsilon.

[a]H-F Epsilon = .504. [b].680. [c].453.

*$p < 0.05$. **$p < 0.01$. ***$p < 0.001$.

Table 3

Tukey's HSD Multiple Comparison Summary Table for Cardinal Directions (Experiment 2)

Comparison	Mean Difference
Fixate Center vs. Track Target	.190
Track Planar vs. Track Target	1.813*
Track Planar vs. Fixate Center	1.623*

*$p < 0.05$.

Table 4

Analysis of Variance Summary Table for Diagonal Directions (Experiment 2)

Source	df	SS	MS	F
Within-Subjects				
Fixation (A)[a]	2	28.514	14.257	28.688**
Error	8	3.976	.497	
Speed Gradient (B)[b]	2	.239	.119	1.221
Error	8	.782	.098	
A x B[c]	4	.169	.042	.391
Error	16	1.727	.108	

Note. Due to the possibility of the sphericity assumption being violated, all F values were compared against critical values adjusted by the Huynh-Feldt epsilon.

[a] H-F Epsilon = .504. [b] .941. [c] .393.

*$p < 0.05$. **$p < 0.01$. ***$p < 0.001$.

Table 5

Tukey's HSD Multiple Comparison Summary Table for Diagonal Directions (Experiment 2)

Comparison	Mean Difference
Fixate Center vs. Track Target	.093
Track Planar vs. Track Target	1.733*
Track Planar vs. Fixate Center	1.64*

*$p < 0.05$.

Appendix E

Summary Table for Experiment 3

Table 1

Analysis of Variance Summary Table for Cardinal Versus Diagonal Directions (Experiment 3)

Source	df	SS	MS	F
Within-Subjects				
Direction (A)[a]	1	1.190	1.190	6.994
Error	4	.681	.170	
Task (B)[b]	1	27.948	27.948	11.348*
Error	4	9.851	2.463	
Speed Gradient (C)[c]	2	.770	.385	1.175
Error	8	2.622	.328	
A x B[d]	1	.925	.925	4.812
Error	4	.769	.192	
A x C[e]	2	.229	.115	2.790
Error	8	.328	.041	
B x C[f]	2	.881	.440	1.331
Error	8	2.648	.331	
A x B x C[g]	2	.108	.054	2.770
Error	8	.156	.020	

Note. Due to the possibility of the sphericity assumption being violated, all F values were compared against critical values adjusted by the Huynh-Feldt epsilon.

[a]H-F Epsilon = 1.000. [b]1.000. [c].769. [d]1.000. [e].540. [f].934. [g].609.

$^{*}p < 0.05$. $^{**}p < 0.01$. $^{***}p < 0.001$.