Catching Balls: What Visual Cues Are Used to Judge the 3-D Trajectory of a Moving Object?

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Abstract

We created a virtual ball-catching task that simulates a fly ball launched from a central point and had human subjects predict where the ball will land. Many properties in the task were varied such as the ball's rate of change in size, the ball's absolute image size, the presence of a background grid as a reference point and the portion of the flight trajectory shown to the viewer. Analysis of subjects' final landing site predictions and mouse tracks as a function of our variables helped us determine which visual cues are used to perform this task. The changing-size cue and absolute ball size cue are relevant in solving this task. In general, larger balls, which included artificially inflated balls, were judged to land closer to the viewer relative to the balls' true landing site. Smaller balls, including artificially deflated balls, were judged to land farther away from the viewer relative to the balls' true landing site. The presence of a background grid does not affect landing site predictions. The experiment where we varied the portion of the trajectory shown to the viewer provided insight on catching strategies that subjects use. Some subjects clearly anticipated where the ball would land; others tracked the ball's projection on the ground plane as the ball evolved in its trajectory.

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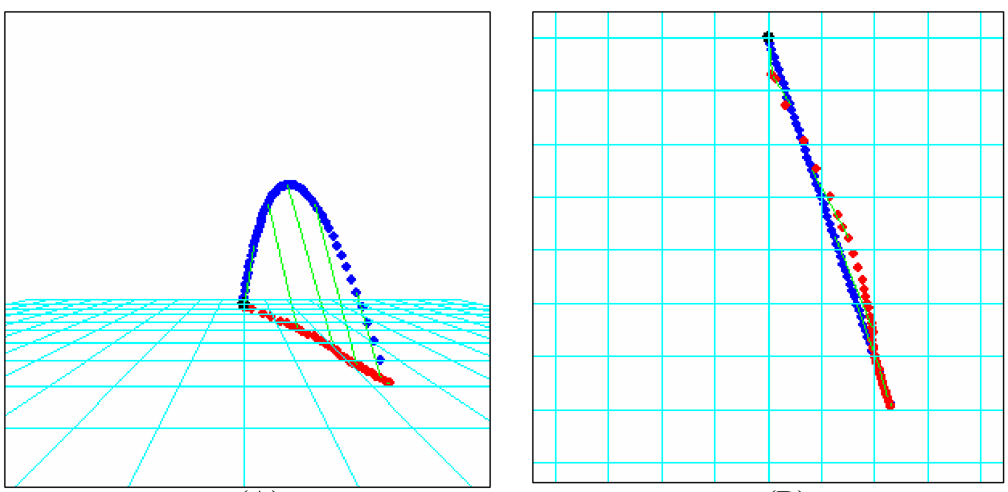
Chapter 1. Introduction

The act of successfully catching a fly ball is a fascinating feat when analyzed in terms of the interaction between the human visual system and the motor movements involved in this seemingly ordinary task. Within half a second after a ball is launched, a fielder is able to judge the ball's three-dimensional (3-D) trajectory and initiate appropriate motor movements towards the ball's eventual landing site (Oudejans et al. 1997). What visual cues are used to determine the 3-D trajectory of the ball from the changing 2-D image it projects on the retina? To what extent can an observer predict where the ball will land? This thesis examines these questions through an analysis of human performance on a virtual ball-catching task in which subjects view a moving ball on a computer monitor and control a catching palette on the screen to intercept the ball. By manipulating the visual cues available in the display and measuring the effects of these manipulations on human performance, we can explore which visual cues are relevant to this task.

There are a number of visual cues available to the fielder catching a fly ball. For example, as the ball moves closer to the viewer, the image of the ball expands in size. The background scene provides a 3-D reference frame for the ball's motion. Under the influence of gravity, the ball follows a parabolic trajectory in 3-D that depends on the initial 3-D launch velocity. The projected 2-D image of this trajectory serves as a visual cue for the ball's true 3-D motion. We manipulated these cues in the virtual ball catching task we created.

The catching task is similar to that in Saxberg's (1987b) study (Figure 1): a ball appears to be launched upwards from a central position on a floor, moving under the influence of gravity toward a landing site that is closer to the viewer. The viewer indicates where he or she thinks the ball will land by moving a virtual catching palette under the control of the subject's computer mouse. The sizes of the ball and the catching palette in the image change as they move, to reflect their real-world perspective projection as these objects come closer to the viewer. An optional floor grid provides an explicit cue to the 3-D ground plane. During training conditions for the subjects, the ball follows a complete parabolic trajectory. During an experimental condition, the ball is visible for only a portion of its trajectory. The position of the catching palette is recorded in each successive frame with respect to two movement views, the image and bird's-eye views. The image view corresponds to the perspective projection of the ball-catching environment onto the computer screen (Figure 1A). The bird's-eye view corresponds to the aerial view of the 3-D environment (Figure 1B).



(A) (B)

Figure 1. Image view (A) and birds'-eye view (B) of the approaching ball and mouse tracks in the ball-catching task. Blue dots show a sequence of ball positions at a fixed time interval for a sample trajectory and red dots show a sequence of mouse positions corresponding to the subject's movement of the catching palette. The green lines connect ball and mouse positions that occurred at the same moment in time. During an actual trial, only one dot corresponding to the ball position is visible at any given time, the mouse tracks are hidden, the moving ball is white, the grid and catching palette are different shades of gray and the background is black.

In this task, the speed, absolute size, rate of change of size and the initial and final landing positions of the ball, as well as the presence of a background floor grid and the portion of the trajectory displayed can all be manipulated. This study explored the effects of three visual cues: (1) the changing-size cue, (2) the presence of a background grid as a static reference frame and (3) the portion of the trajectory viewed. Performance was evaluated by examining the accuracy of subjects' judgments of the final landing site of the ball. The subjects' mouse tracks that were recorded as the subject attempted to catch the ball were also analyzed.

This thesis shows that manipulation of the changing-size cue significantly affects the viewers' predictions of where the ball will land, which is consistent with findings from previous studies (Todd 1981; Saxberg 1987b; Brouwer et al. 2006). Additionally, this thesis shows that the absolute size of the ball alone affects viewers' perceptions of where the ball will land. The presence or absence of a background reference frame does not affect the viewers' performance in a significant way. Experiments varying the portion of the trajectory viewed show a consistent but insignificant increase in uncertainty and a lack of systematic bias in the ball's landing site with shorter viewing time. The mouse tracks also reveal that observers used different strategies to solve this virtual catching task.

Chapter 2. Background

Many theoretical and empirical studies have examined the relevant visual cues in a ball-catching task. Both theoretical and empirical methods have used a variety of ball-catching environment representations, some solving the task using 2-D image cues and others using 3-D information derived from the 2-D image. We will define the physical environment and geometric calculations for our study before discussing theoretical models and previous perceptual experiments.

2.1 Free-fall motion and its image projection

We defined a 3-D coordinate frame with the viewer's eye as the origin: the positive x axis is directed horizontally to the right; the positive y axis is directed vertically upward; and the positive z axis points straight ahead into the plane of the monitor. Assuming that the ball is launched from position (X_0, Y_0, Z_0) with initial velocity (V_x, V_y, V_z) and undergoes free-fall motion under the influence of gravity g, the position of a ball at a given time t in a frictionless environment is given by the following equations:

$$X = X_0 + V_x t \quad (1)$$

$$Y = Y_0 + V_Y t - 0.5gt^2 \quad (2)$$

$$Z = Z_0 + V_z t \quad (3)$$

The ball position (X, Y, Z) is specified in meters, velocity V in m/s, time t in seconds and gravity g is 9.8 m/s^2.

If the ball is launched from a point on the ground plane at $Y = Y_0$, then the ball will land at a non-zero time t_F where $Y = Y_0$, which is,

$$t_F = 2V_Y/g \quad (4)$$

By substituting time, t_F, into the original equations for the ball position, the final landing site (X_F, Y_F, Z_F) of the ball is given as,

$$X_F = X_0 + 2V_xV_y/g \qquad (5)$$

$$Y_F = Y_0 \qquad (6)$$

$$Z_F = Z_0 + 2V_zV_y/g \qquad (7)$$

From a 2-D image of the scene, the visual system does not have direct access to the initial position and velocity of the ball in 3-D space. Instead, the visual system needs to infer the properties of the 3-D trajectory from the 2-D image. Some studies assume perspective projection onto a 2-D image plane located at focal distance f from the center of projection. In this case, the image location (x, y) is given by:

$$x = f\,(X_0 + V_xt) / (Z_0 + V_zt) \qquad (8)$$

$$y = f\,(Y_0 + V_yt - 0.5gt^2) / (Z_0 + V_zt) \qquad (9)$$

In our experiment, these equations were used to compute the projection of the virtual 3-D trajectory of the ball as well as the background grid and catching palette onto the flat computer screen. This projection approximates the image that an observer would see when viewing a real 3-D environment, and may yield some distortion for a wide field of view.

Other studies assume spherical projection in which the image position is defined in terms of two optical angles (Φ, θ) in the horizontal and vertical directions:

$$\Phi = tan^{-1}(X/Z) \qquad (10)$$

$$\theta = tan^{-1}(Y/Z) \qquad (11)$$

2.2 Theoretical models of 3-D trajectory estimation

Saxberg (1987a) shows how the initial 3-D position and velocity of the ball can be recovered from the projected image trajectory *(x, y)* using three different methods. The initial conditions can be recovered directly using the first and second temporal derivatives of *(x, y)* at a single moment in time, but this computation is extremely sensitive to errors in the derivative measurements. Filtering the image trajectory with a low-pass filter yields some improvement in the performance of this method. A second method uses a least-squares technique which determines the initial conditions that yield an image trajectory that best fits the observed trajectory. A third method uses a parameter estimation technique from optimal signal processing theory to estimate the initial position and velocity. Computer experiments show improved performance of these methods as more of the image trajectory is incorporated into the computation. For all three methods, the initial conditions can be used to predict the final landing site using the equations of motion.

A number of studies address baseball outfielders' running behavior when the players are preparing to catch a fly ball. Outfielders do not immediately go to a fly ball's landing site, but instead employ tracking schemes that are self-correcting (McLeod and Dienes 1996). One such scheme is called the optical acceleration cancellation (OAC) strategy. Assuming that the ball is coming straight toward the fielder, following a vertical line in the projected image, the ball will appear to decelerate if it is going to land in front of the observer and accelerate if it will land behind the observer. Using the OAC strategy, the observer constantly moves in the forward or backward direction to keep the vertical acceleration of the ball equal to zero (Chapman 1968). A second scheme is the linear optical trajectory (LOT). If the ball is thrown toward the side of the observer, the observer can move in a direction that cancels out the curvature of the projected image path of the incoming ball (McBeath, Shaffer and Kaiser 1995). While using the LOT strategy, the observer moves so that the ball follows a straight line from the observer's point-of-view. In both the OAC and LOT schemes, the observer continually adjusts his position throughout the ball's trajectory and does not appear to predict the ball's future landing site while the ball is in flight. These two strategies use visual cues defined in a viewer-centered, moving coordinate frame; in contrast, our experimental setup gives the observer a fixed view of the scene in a static coordinate frame. We observed, however, that some of our subjects appear to track the ball's projected path on the ground, continually adjusting the position of the mouse in correspondence with the ball's motion, rather than making an early prediction of where the ball will land and making a rapid movement to this landing site. This continuous tracking behavior may be analogous to the tracking behavior of outfielders catching a fly ball.

Other studies have shown that it is possible to determine a ball's instantaneous 3-D movement given very limited visual information. Given two image frames showing an object's movement, some models infer the object's 3-D direction of motion relative to the observer. Regan and Kaushal (1993) and Welschman et al. (2004) show that given the initial angular size of the object θ_0, the object's changing size θ, and its angular position with regard to the viewer α, the object's 3-D direction of motion β can be approximated using the equation:

$$\beta \approx tan^{-1}(\theta_0 \sin \alpha / (\theta_0 - \theta \cos \alpha)) \qquad (12)$$

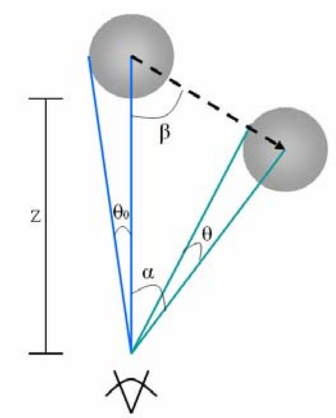


Figure 2. Birds' eye-view of an observer viewing the progressive movement of a ball.

A birds'-eye view of the relevant angles is shown in Figure 2. The velocity in the Z direction can also be approximated given the initial distance of the object from the viewer, Z_0:

$$V_z \approx (Z_0 d\theta / dt) / \theta_0 \qquad (13)$$

The above analysis assumes that the ball is moving with a constant speed and direction of motion, and that θ is small. Information about the ball's 3-D direction of motion can be used to help predict a ball's landing site. Given the orientation of the plane of the object's 3-D movement trajectory and the ground plane, it is possible to construct a line where these two planes intersect. This line is the projected linear path of the object along the ground (Figure 3).

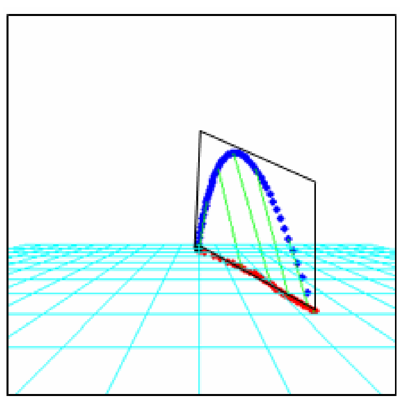


Figure 3. The plane of the 3-D movement trajectory plane intersects with the ground plane at the projected linear path of the 3-D trajectory on the ground plane. In the above trial, the subject's mouse tracks follow this linear path.

2.3 Perceptual studies of 3-D motion recovery

This thesis focuses on three questions related to the analysis of a free-fall flight trajectory: (1) How does the changing-size cue influence the perception of 3-D motion? (2) What is the role of a static reference frame such as a grid depicting the floor in our displays? (3) How does performance change as the trajectory evolves over time? The last question indirectly addresses what visual cues are used, as the viewing of short trajectory segments limits the visual cues available in the displays. Question (3) also addresses whether subjects predict the launched object's landing site early in the trajectory or whether they instead continually track the object, employing a self-correcting strategy while the ball is visible, to arrive at the correct landing site at the moment the object would have landed. We now consider previous perceptual studies relevant to answering the aforementioned questions.

2.3.1. Changing-size cue

Saxberg (1987b) conducted perceptual experiments in which subjects viewed computer displays of the flight of a ball following a free-fall trajectory. In his study, subjects were instructed to move a catching palette under the control of the computer mouse to where the ball would land. Subjects viewed the full trajectory with or without the changing-size cue: with the changing-size cue, the image size of the ball changed as it moved in depth, as it would under natural viewing; without the changing-size cue, the ball remained a constant size in the image. Saxberg found that when the changing-size cue was not available, the landing site predictions were less precise.

Todd (1981) also examined the effects of the changing-size cue. In Todd's experimental setup, subjects viewed a computer display of the growing outline of a gradually approaching square following a free-fall trajectory. The trial was terminated before the peak of the square's trajectory was viewed; subjects judged whether the square would have landed in front or behind them. When the changing-size cue was removed, the square appeared instead as a small dot that remained a constant size. Consistent with Saxberg's findings, Todd found that subjects' performance was significantly degraded without the changing-size cue. The same performance degradation was observed in a subsequent experiment where the trial was terminated just after the peak of the trajectory was shown.

Artificial inflation or deflation of an approaching object also tests the relevance of the changing-size cue. Brouwer et al. (2006) showed the first 319ms of a movie of artificially inflated or deflated tennis balls coming towards the viewer while the balls underwent free-fall trajectories. Subjects were asked to judge whether the balls would land in front of or behind them for the different size manipulations. Systematic errors were observed, but the authors argued that the errors were a function of the vertical angular velocity and not of the balls' rate of expansion per se. Experiments were also conducted to determine whether the absolute size of the approaching ball influenced the subjects' landing site judgments. The results suggested that small balls were more likely to be judged as landing in front of the observer, while large balls were more often judged to land behind the observer relative to the balls' true landing site.

The absolute size of the ball also has a notable effect on judgments of lateral movement. In a study by Peper et al. (1994), subjects judged the reachability of balls that passed by their body on one side. It was found that large balls were judged to be more reachable than small balls, suggesting that large balls are perceived to be moving in a 3-D direction corresponding to smaller β (Figure 2) relative to small balls undergoing the same trajectory through space.

Regan and Kaushal (1993) measured perceptual thresholds for discriminating the 3-D direction of motion of an object from its translation and expansion in the image, and found thresholds in the range of 0.03-0.12° for both direct approach and oblique directions of motion toward the observer.

2.3.2. Static reference frame

Two studies (Saxberg 1987b; Oudejans et al. 1999) show that a static reference frame for a moving trajectory has minimal effect on a subject's judgment of where an object will land. In Saxberg's experiment, subjects viewed a full trajectory with or without a background floor grid. The results showed no significant difference between the two conditions. Oudejans et al. launched luminous fly balls in the dark, effectively removing a visual background cue, and observed that outfielders successfully ran towards the correct landing sites, as they did in full lighting conditions when a visual background was available.

2.3.3 Portion of the trajectory viewed

Studies cited earlier suggest that with brief viewing of the initial segment of a ball's movement trajectory, observers can judge whether a ball will land in front of or behind them (Todd 1981; Brouwer et al. 2006). In Todd's study, there was no significant degradation in performance when the object disappeared before reaching its peak. Furthermore, Oudejans et al. (1997) show that outfielders initiate appropriate running movements only 500ms after a ball is launched.

The question of whether subjects are able to predict the correct landing site at the outset of the ball's trajectory, or if continuous tracking is necessary to arrive at the landing site when the ball lands, was addressed by McLeod and Dienes (1996). Balls were launched at varying speeds and it was observed that outfielders ran at a speed that kept their acceleration constant instead of observing the trajectory and running to a predicted landing site immediately. This study suggests that outfielders do not predict the landing sites of balls undergoing free-fall trajectories, but rather employ a continually self-correcting tracking scheme that brings the outfielder to the correct landing site at the moment the ball lands. In their study of reaching movements to intercept a ball passing to the side of an observer, Peper et al. (1994) show that hand movements appear to be continuously geared to optical variables such as the position and velocity of the approaching ball.

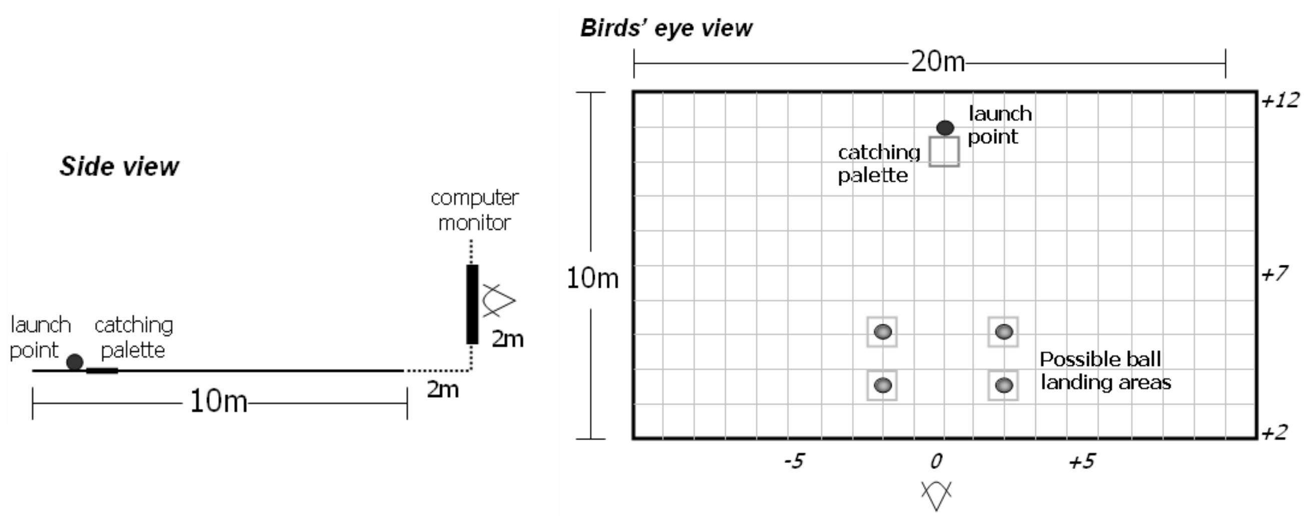
Chapter 3. General Methods

We conducted five experiments, whose conditions are summarized in Table 1. Experiments 1 and 2 explored the role of the changing-size cue in predicting a ball's landing site. Experiment 3 examined whether performance was affected by the presence of the background floor grid. Finally, Experiments 4A and 4B explored how the portion of the trajectory viewed affected performance. This chapter summarizes the general methods used for these experiments. Further details are given in Chapter 4.

The computer simulation was implemented in MATLAB v.7.0 using the Psychophysics toolbox extension (Brainard 1997; Pelli 1997) run on a Gateway NVIDIA GeForce FX 5200 personal computer with a 12x16 inch FFD2020 display screen with 1200x1600 pixels at 96 DPI and a refresh rate of 60Hz. Subjects wore an eye patch and viewed the display monocularly with their self-reported dominant eye. The subject's eye was positioned 2m above the virtual ground plane and 2m away from the edge of the virtual environment (Figure 4A). The background floor grid was removed in Experiment 3 and visible in all other experiments. The background floor spanned a rectangular area 10m in depth and 20m wide with an overlaid supporting grid that divided the projection into 1m x 1m squares (Figure 4B). The ball was launched from a central point located 11m straight ahead of the subject. In Experiments 1-3, the ball moved towards one of four areas of size 0.6m x 0.6m centered at locations (-2, 3.5), (2, 3.5), (-2, 5) and (2, 5) meters in the viewer's coordinate frame (Figure 4B). Specific landing sites were selected randomly within the four areas. In each experimental session, there were an equal number of balls that went to each of the four landing areas. Experiments 4A and 4B used a set of 16 fixed landing sites arranged symmetrically to the left and right.

	Session	Ball Size	Landing Sites	Initial Palette Position	Background Grid	Portion of trajectory viewed in experimental condition
Experiment 1: Changing-size cue	1	Artificial change in 3-D Size: 60%, 100% and 200% 3-D ball sizes: • 0.15m balls grew to 200% • 0.25m balls shrunk to 60% • Equal number of 0.15 and 0.25m balls remained 100% of their size	Randomized within 4 areas	Far	Yes	95%
Experiment 2: Constant ball size	2	No changing-size cue Constant image size: 8, 16 and 24 pixels	Randomized within 4 areas	Far	Yes	95%
Experiment 3: Static reference frame	2	Normal changing-size cue 3D ball sizes: 0.15m and 0.25m	Randomized within 4 areas	Far	No	95%
Experiment 4A: Portion of trajectory viewed	3	Normal changing-size cue 3D ball size: 0.20m	16 fixed landing sites	Far	Yes	65%
	4	Normal changing-size cue 3D ball size: 0.20m	16 fixed landing sites	Far	Yes	45%
Experiment 4B: Portion of trajectory viewed – catching palette moved to a central depth position	5	Normal changing-size cue 3D ball size: 0.20m	16 fixed landing sites	Centered	Yes	65%
	6	Normal changing-size cue 3D ball size: 0.20m	16 fixed landing sites	Centered	Yes	45%

Table 1. Details of experimental setups



(A) (B)

Figure 4. (A) Side view and (B) birds'-eye view of simulated 3-D environment.

Most experiments used two different 3-D ball sizes, 0.15m and 0.25m that remained constant over the trajectory. The initial image sizes of these balls at the launch point were 7.09 and 11.81 screen pixels respectively. The ground velocity was held constant at 4 m/s. For each trial, the ground speed and final landing site were used to determine the total time to complete the trajectory. This information was then used to compute the initial 3-D launch velocity from Equations 4-7. The number of discrete frames for the parabolic path was determined from the total time of the trajectory and the frame rate for the computer software (30 frames per second). Equations 1-3 were used to compute the 3-D location of the ball at each time step. Finally, the location and size of the ball on the 2-D computer monitor were determined using perspective projection (Equations 8-9). As a consequence of perspective, the image of the ball grows in size as it moves toward the viewer. As noted in Table 1, the rate of change of image size was artificially manipulated in Experiment 1 and the image size of the ball was held constant in Experiment 2. In all other experiments, the image size of the ball expanded as it moved, as it would under natural viewing conditions.

After the ball was launched, the subject moved a 0.5 x 0.5m rectangular catching palette over the floor, whose position was controlled by the subject's mouse movements, to catch the ball. In Experiments 1-4A, the catching palette was initially placed near the launch point, and in Experiment 4B, the palette was initially placed at a central location. While the ball was in motion, the observer's mouse position at each successive frame was recorded by the program. The catching palette and the background floor grid were gray on a black background (Figure 5).

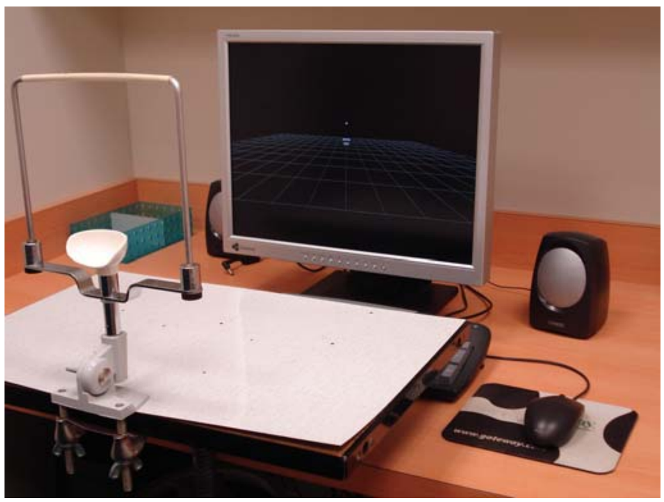


Figure 5. Experimental setup showing the display screen with the catching task simulation, chin rest and computer mouse. Actual experimental sessions were conducted in a dark room.

The experimental sessions were conducted in a dark room. Head motion was restricted with the use of a chin rest placed 16 inches from the display screen. The screen subtended an angle of view of roughly 60°. The ball's image trajectory spanned a smaller region of the monitor, roughly 30°. An experimental session lasted between 30-60 minutes and tested 3 or 4 ball-catching conditions. In each session, the first two conditions were used for training. Both training conditions consisted of 80-96 trials, each lasting between 1.4-2.0 seconds, where subjects received immediate audio and visual feedback on the accuracy of their catches. A catch was considered successful if the ball landed within a distance of 0.05m from the center of the catching palette for the first training condition showing a 100% trajectory. A catch was successful if the ball landed within a distance of 0.15m from the center of the catching palette for the second training condition, which only showed 95% of the trajectory, after which the ball disappeared. These two training conditions were included in all experimental sessions to monitor potential shifts in overall performance over multiple sessions. The remaining one or two conditions in each session tested our experimental conditions that addressed the effects of ball size, background grid and portion of trajectory viewed. Subjects were allowed to take short breaks between conditions.

Subjects were five college-age women who asserted better-than-average visuomotor skills through experience in sports or video games. The subjects reported normal or corrected-to-normal vision. All subjects were naïve as to the purpose of the experiments and participated in all five experimental conditions.

Chapter 4. Experiments

Experiments were conducted in 6 sessions, roughly 2 weeks apart, over an 11 week period. Table 1 shows the conditions used for each session. The experimental conditions for Experiment 1 were conducted after subjects reported to be comfortable with the 3-D environment of the task. Subjects' performance over the 6 sessions was monitored. Figure 6 summarizes errors in landing site predictions in the horizontal (A) and depth (B) directions for the first training condition over the 6 sessions. The errors were calculated by projecting the 2-D mouse coordinates on the screen back onto the floor to determine 3-D horizontal and depth coordinates. There is an overall improvement in performance from Sessions 1-3, but performance is consistent from Session 3 onwards (Figure 6).

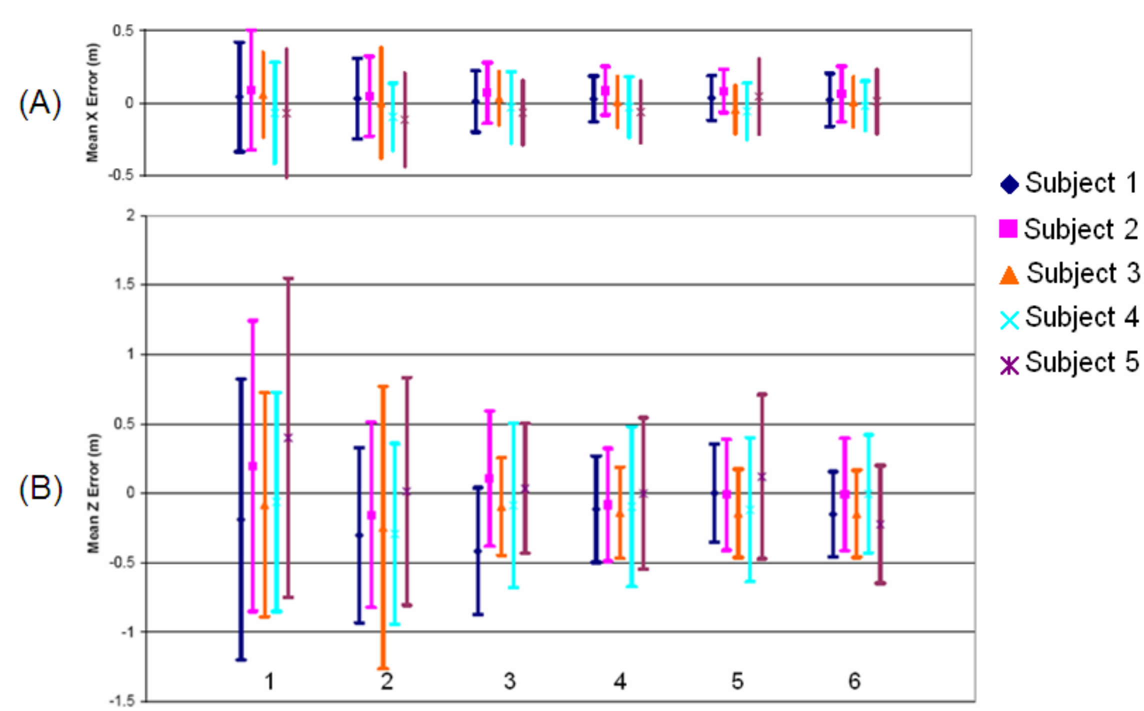


Figure 6. Landing site mean errors showing standard deviations in meters in the horizontal (A) and depth (B) directions within the five subjects over 6 experimental sessions.

This chapter summarizes specific hypotheses and methods for each of the four experiments listed in Table 1. We also present the results of each experiment and discuss the results in relation to our hypotheses.

4.1 Experiment 1: Changing-size cue

As discussed in Chapter 2, previous theoretical and empirical studies demonstrated the importance of the changing-size cue. Saxberg (1987b) compared subjects' catching behavior with the presence or absence of the changing-size cue, while Todd (1981) compared perceptual judgments of landing sites under these two conditions. Brouwer et al. (2006) determined that balls which have undergone an artificial decrease in rate of expansion were judged to land further in front of their true landing site. Balls whose rate of expansion was artificially increased were judged to land further behind their true landing site. Experiment 1 is similar to that of Brouwer et al.'s wherein we artificially increased or decreased the changing-size cue.

Equation 12 shows that the 3-D direction of motion of an object relative to the viewer depends on its evolving image size θ. Equation 13 relates the object's velocity in depth, V_z, to its rate of change of image size $d\theta/dt$. Based on these equations, increasing the image size, θ, leads to a decrease in angular direction of motion, β, and an increase in perceived velocity. In this experiment, we manipulated the 3-D size of the ball to be artificially inflated or deflated as it moves, resulting in an increase of θ or $d\theta/dt$ relative to natural viewing conditions. We therefore expect systematic errors in the perceived landing site of the ball: Artificial inflation should lead to a decrease in perceived angular direction of motion and an increase in perceived velocity in depth, resulting in the perception that the ball is landing closer to the viewer, both horizontally and in depth.

Similarly, artificial deflation should result in the perception that the ball is landing further away from the viewer, both horizontally and in depth.

4.1.1 Methods

The experimental setup for this experiment followed that of the general methods section. More specifically, the rate of change of the size of the ball in 3-D in the simulation task was artificially manipulated to be 60% (deflation), 100% (normal) or 200% (inflation) of the original ball size by the end of the trajectory. There were 10 trials for each of these three manipulations for each of the four predetermined landing areas, totaling 120 trials.

While the ball was in flight, the ball size changed with equal increments or decrements per frame, based on the calculated final ball size. The balls with an initial 3-D size of 0.15m were manipulated to artificially inflate to 200% while the 0.25m balls were manipulated to artificially deflate to 60%. There were an equal number of 0.15m and 0.25m balls whose 3-D size remained constant (100%). Balls that were 0.15m landed in the areas that were centered at a distance 3.5m away from the viewer, while 0.25m balls landed in the areas that were centered at a distance 5m away from the viewer.

During each experimental trial, the subject was only shown the first 95% of the trajectory, after which the ball disappeared. The subject indicated where the ball would land by moving the catching palette and clicking the mouse on this landing position. There was no feedback during the experimental session.

4.1.2 Results and Discussion

Informal observation of the subjects' landing site predictions suggests that the manipulations of the changing-size cue had a systematic effect on subjects' perception of where the balls would land. Figure 7 shows data for one subject, both in the image view (Figure 7A) and birds'-eye view (Figure 7B). Data for the other four subjects are provided in the Appendix A. The artificially deflated balls (red dots) were judged to land farther away from the viewer, both horizontally and in depth relative to the ball's target landing site (black dots). The artificially inflated balls (blue dots) were judged to land closer to the viewer, both horizontally and in depth relative to the ball's target landing site. Balls that exhibited the normal changing-size cue had perceived landing sites that were scattered throughout the deflated and inflated balls. This trend was evident in all four landing areas for all subjects and is consistent with our predictions based on findings from similar previous studies.

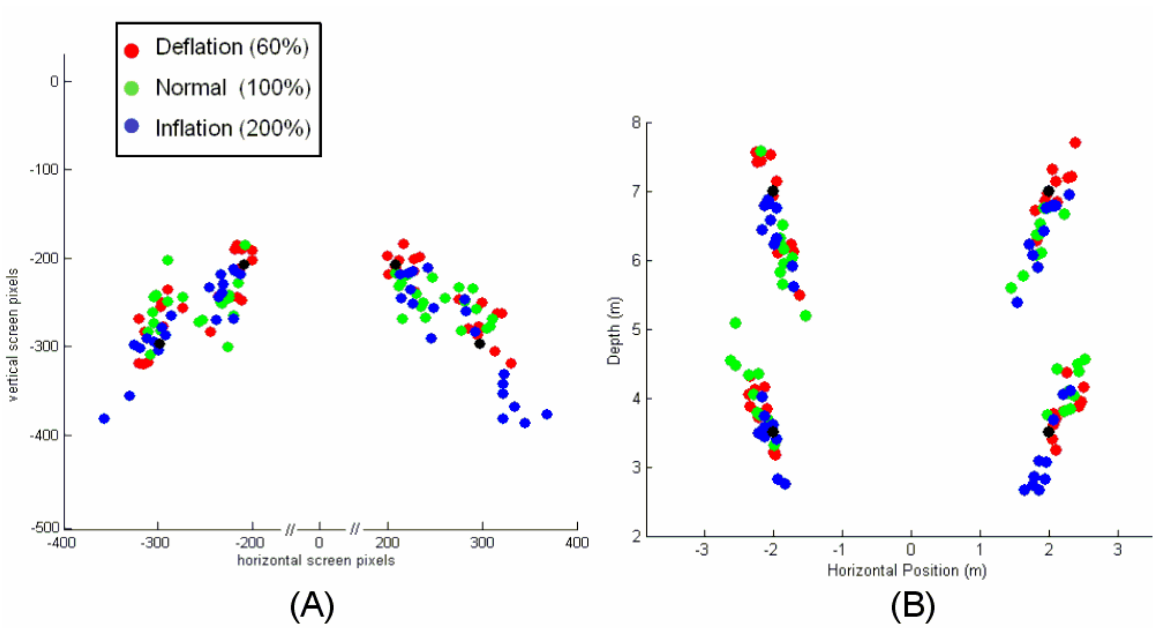


Figure 7. (A) Image and (B) Birds'-eye views of Subject 3's landing site predictions classified between the four predetermined landing areas during the changing-size cue experiment. The randomly positioned landing sites within each of the four areas were shifted to a common location represented by the black dot in the figure. The landing areas that are far away from the viewer (-2, 5) and (2,5) have been shifted to (-2, 7) and (2,7) to separate the data from the close landing site predictions. The placement of each data point (red, green and blue) reflects the error in predicting the landing site relative to its actual location. Subject 1's landing site predictions are representative of the four other subjects' catching behavior, as shown in statistical analyses. Other subjects' data are included in the Appendix A.

The distribution of errors in the birds'-eye view has an elongated pattern that is due in the part to the perspective projection. This factor is illustrated in Figure 8. Figure 8A shows an image view of the floor grid with the blue dot representing the true landing site. The red dots show a set of erroneous judgments of the landing site. If these erroneous judgments are projected onto the ground plane and viewed from above, they span an elongated region on the ground with an oblique orientation relative to the floor grid. The distribution of error shown for Subject 3 in the birds'-eye view in Figure 7B has an elongated distribution around the true landing site. There is still a bias, however, in the placement of the dots for the three size manipulations with the deflated balls (60%, red dots) judged to land farther away from the viewer, the inflated balls (200%, blue dots) judged to land closer to the viewer and normal balls (100%, green dots) distributed throughout the inflated and deflated balls.

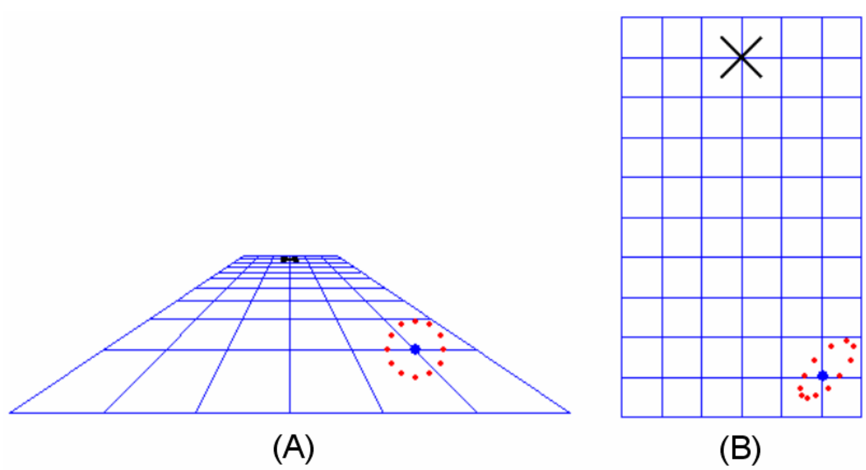


Figure 8. (A) Image and (B) Birds'-eye views of sample landing site (blue dot) and erroneous judgments of the landing site (red dots).

We analyzed the data quantitatively, both in terms of error in the judgments of the depth component of the landing sites and in terms of the 3-D direction of motion, β, implied by the perceived landing sites.

The mean errors from all four subjects show that there was a systematic bias in the perceived landing site depending on the artificial rate of size manipulation (Figure 9). Subject 1's data was removed from this analysis due to her individual unequal variance between the 60% and 200% manipulations. A one-way ANOVA, pooling data within all four subjects for each condition, showed a close to significant difference in mean landing site prediction error between the 60% and 200% manipulations ($p=0.061$). All other comparisons, between the 60% and 100% and between the 100% and 200% manipulations, showed no significant differences in mean landing site errors.

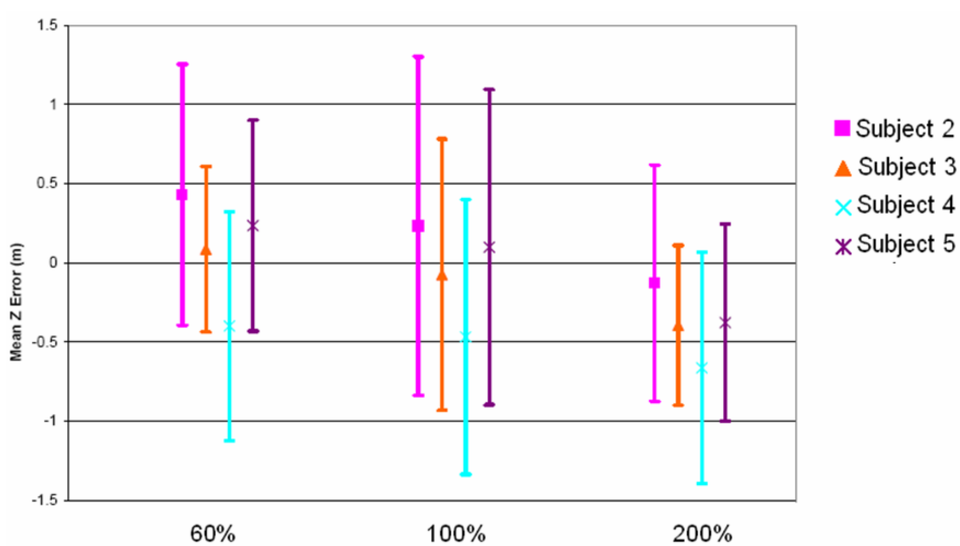


Figure 9. Mean depth errors showing standard deviations in meters for landing site predictions of four subjects in artificial deflation (60%), artificial inflation (200%) and normal (100%) changing-size cues.

To analyze the data further, we determined the perceived 3-D direction of motion β for each data point (Figure 10). The mean β errors were calculated and normalized so that positive mean errors reflected landing site predictions farther away from the viewer relative to the ball's true landing site and negative mean errors reflected landing site predictions closer to the viewer relative to the ball's true landing site. We pooled the data for the four landing areas and five subjects and tested whether the mean β errors for the three size manipulations (60%, 100% and 200%) were significantly different. In this case, the comparison between the 60% and 200% manipulations was significantly different ($p < 0.05$, Figure 11). Data comparing the 100% to 200% manipulations were close to significant ($p=0.077$) while data comparing 60% to 100% manipulations remained insignificant ($p=0.584$). In this analysis, we are confident that the results are not artifacts of the skewed perspective suggested in Figure 8. Small β values, which were observed in the artificial inflation condition, clearly translate to balls perceived to land closer to the viewer regardless of the elongated orientation of the landing site predictions. Large β values, which were observed in the artificial deflation condition, clearly indicate that balls were perceived to land farther away from the viewer. Further data analysis using β values was conducted.

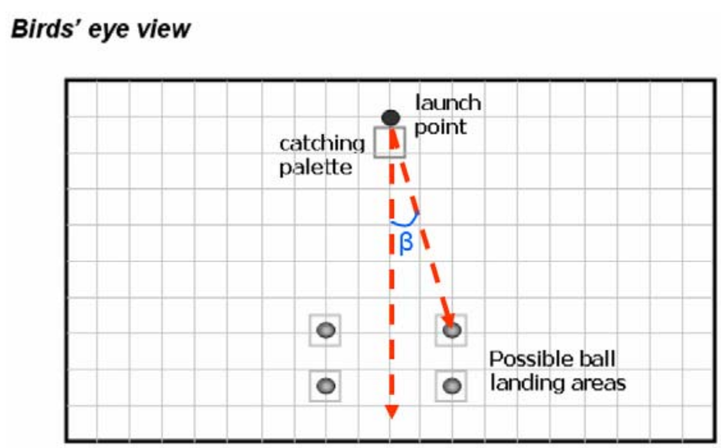


Figure 10. 3-D direction of motion, β, determined in terms of the initial launch point and the predicted landing sites.

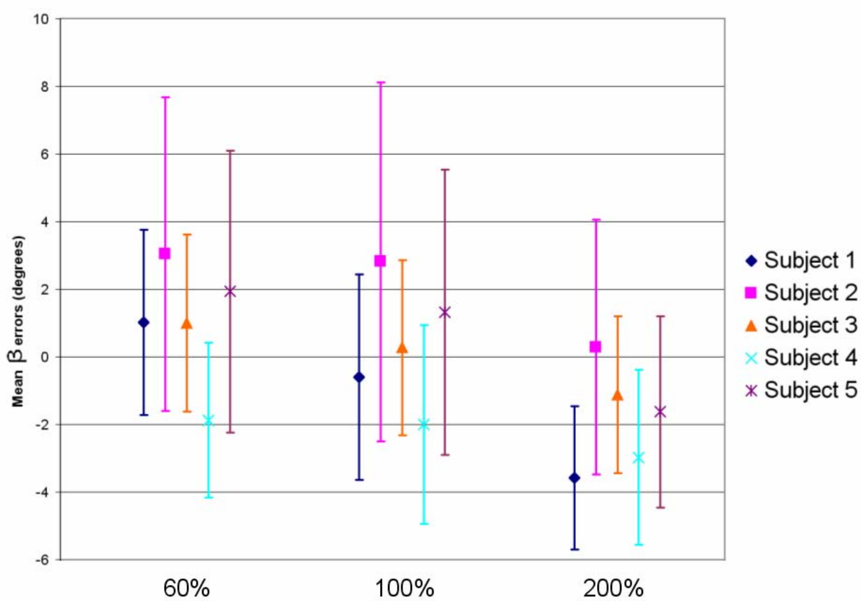


Figure 11. Mean error in β in degrees for landing site predictions of five subjects in artificial deflation (60%), artificial inflation (200%) and normal (100%) changing-size cues.

To determine whether the landing area toward which the ball was moving had an effect on the viewers' predictions, data were again pooled across the five subjects, but data for the four landing areas were analyzed separately. Data analysis showed that the perceived angular direction of motion, β, for balls that moved toward landing areas close to the viewer – those that were 3.5m away from the viewer – was statistically different for each of the three manipulations except for the 60% to 100% manipulations for the right region ($p > 0.05$). The five other β comparisons for the close landing areas – 60% to 100% on the right region, 60% to 200% and 100% to 200% for both left and right regions – were all significantly different ($p < 0.05$).

Comparing the β value for the left and right regions showed no discernible trends. The left and right regions for the far landing areas – those that were 5m away from the viewer – did not show any significant differences ($p > 0.05$) except for the 60% to 100% manipulations for the left region ($p < 0.05$).

The results of this experiment are consistent with what we would expect if the rate of change of image size was used to compute the 3-D motion of the ball. In this experiment, however, the deflated balls generally had a smaller final ball size compared to the inflated balls which were generally larger before they disappeared. Changes in the perceived landing site could be due to differences in the final image size of the ball, rather than the differences in the rate of change of image size per se. To address this potential confounding factor, a second experiment was conducted, where the changing-size cue was removed completely.

4.2 Experiment 2: Constant ball size

Saxberg's (1987a) theoretical study shows that the changing-size cue is not essential for recovering a ball's eventual landing site. The ball's image position and motion over time are sufficient to determine the 3-D launch velocity, from which the ball's eventual landing site can be determined. The perceptual experiments of Saxberg (1987b) and Todd (1981), however, show that when the changing-size cue is removed, there is greater uncertainty in subjects' predicted landing sites. Brouwer et al. (2006) conducted experiments with the changing-size cue present, but with different 3-D ball sizes. For balls undergoing the same trajectory, larger balls (volleyballs) were perceived as landing behind their true landing sites while small balls (tennis balls) were perceived as landing in front of their true landing sites. These findings show a systematic bias as a function of absolute ball size. Peper et al. (1994) also showed a systematic bias in perceived 3-D direction of motion for different ball sizes.

We extended these findings further by conducting an experiment without the changing-size cue but with different absolute ball image sizes. Our hypothesis comes in two parts: (1) consistent with studies by Saxberg (1987b) and Todd (1981), maintaining a constant ball size should result in subjects' greater uncertainty in predicting landing sites compared to their predictions when the changing-size cue is present, and (2) consistent with the studies of Brouwer et al. (2006) and Peper et al. (1994), there should be a systematic bias as a function of the different absolute ball sizes in the experiment. The confirmation of hypothesis (1) would strengthen our conclusion from Experiment 1 that the rate of change of size is a relevant visual cue. The confirmation of hypothesis (2) however, would show that the different ball sizes used in Experiment 1 may have influenced our results and that additional experimentation which addresses the changing-size cue without using different ball sizes should be conducted.

4.2.1 Methods

Procedures followed those of Experiment 1, with the exception that the balls remained a constant image size throughout the entire trajectory. Three ball sizes were tested: small, medium and large corresponding to balls that were 8, 16 and 24 screen pixels in diameter. There were an equal number of the three ball sizes that landed in each of the four predetermined landing areas. Trials with the three ball sizes were randomly interleaved within each experimental run.

4.2.2 Results and Discussion

Even with the constant ball size, there was a strong impression of a 3-D trajectory. Subjectively, there was an impression of a slight shrinking of the ball over time, perhaps induced by the background grid. In our presentation of the results, we consider the issues of certainty and bias separately.

4.2.2.1 Certainty in landing site

Data from this constant ball size experiment for all five subjects for all three ball sizes and for all four landing areas were pooled together. For comparison, the same pooling was done on data from Experiment 3, for the condition in which two different ball sizes underwent the normal expansion in the image. The standard deviations from these two data sets were compared to see if there was greater uncertainty in the constant ball size predictions compared to those with the normal changing-size cue. The standard deviation for performance in the depth direction without the changing-size cue was not significantly different from when the changing-size cue was present ($p > 0.40$). Contrary to previous findings, subjects were equally uncertain about the ball's eventual landing site with or without the changing-size cue.

When the landing site predictions were pooled as previously stated but ball sizes were kept separate, the standard deviation comparisons were still not significantly different. In this case, we found no significant difference comparing the standard deviations of the three ball sizes ($p > 0.40$, Figure 12). Within predictions with the normal changing-size cue, the two ball sizes also have no significant difference in standard deviations ($p > 0.97$). When the constant ball size standard deviations were individually compared to the standard deviations of balls when the changing-size cue was present, the standard deviations were not significantly different ($p > 0.05$). This suggests that subjects' certainty in predicting the landing sites is not affected by the absence of the changing-size cue.

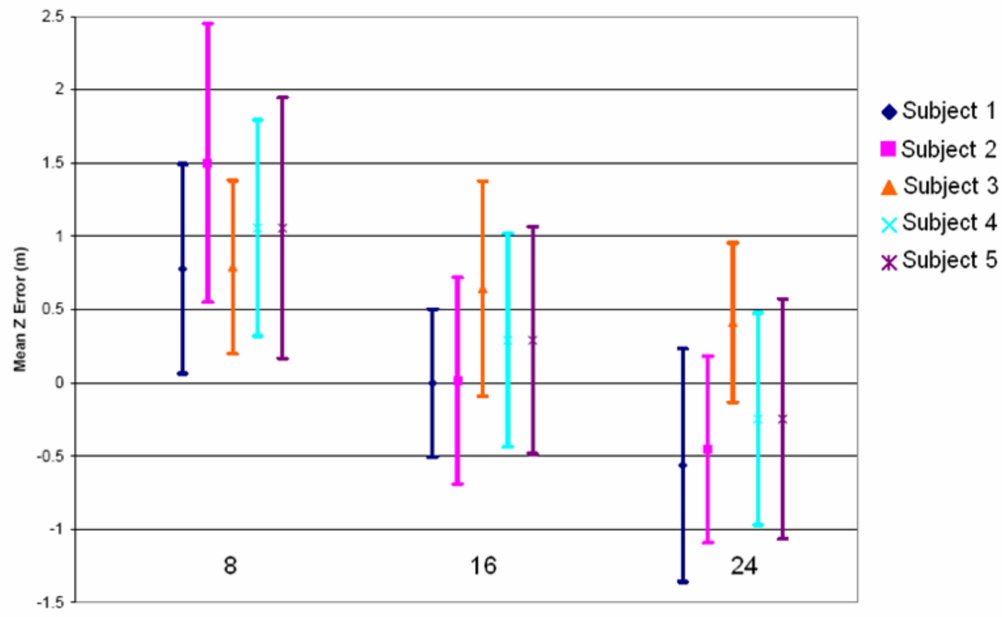
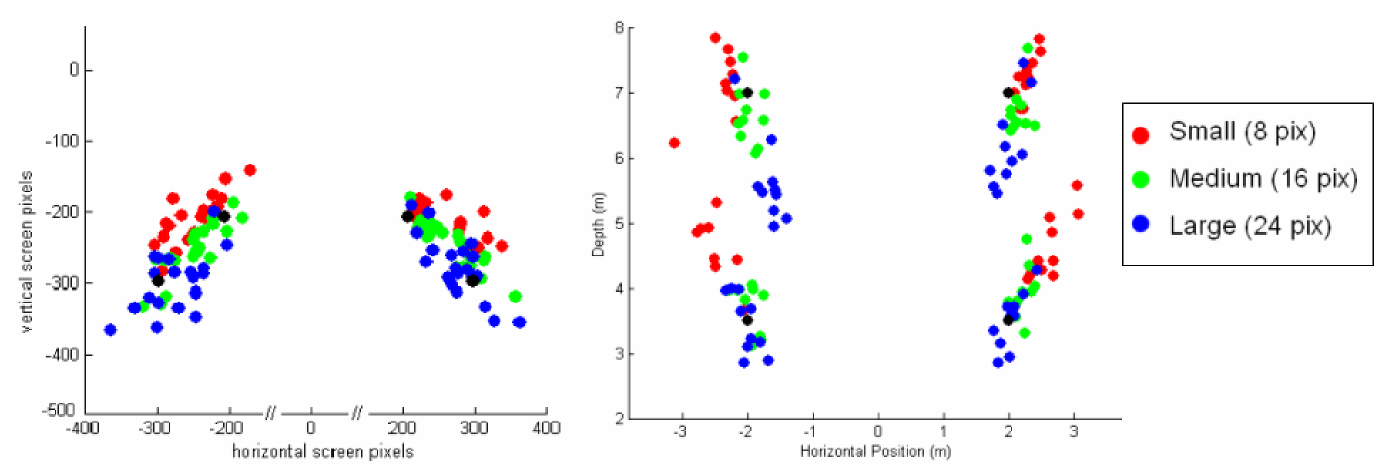


Figure 12. Mean depth error showing standard deviations in meters of landing site predictions of five subjects in the 8, 16 and 24 constant ball size conditions.

4.2.2.2 Systematic bias according to ball size

The results for Subject 1's predicted landing sites for the three different constant ball sizes are shown in Figure 13. Data for the other four subjects are provided in Appendix B. Informal observation shows that the absolute ball size affected subjects' landing site predictions. Small balls (red dots) were perceived to land further away from the viewer in the depth direction. Large balls (blue dots) were perceived to land closer to the viewer in the depth direction. Judgments for medium balls (green dots) were clustered in between those for the small and large balls. One-way ANOVA tests pooling results for all subjects for the four landing sites verify most of these observations. Small balls were perceived to land further away in the depth direction compared to medium and large balls ($p < 0.05$ and $p < 0.01$ respectively). Landing site predictions in the depth direction comparing medium and large balls were not significantly different ($p=0.21$).



(A) (B)

Figure 13. Image view (A) and birds'-eye view (B) of Subject 1's landing site predictions classified within the four predetermined landing sites during the absolute ball size cue experiment. Subject 1's landing site predictions are representative of the four other subjects' catching behavior as shown in statistical analyses.

These results were also analyzed in terms of β, comparing performance for both the different ball sizes and for the different landing areas. We arrived at the same statistical results showing that the comparisons between the small and medium balls as well as between the small and large balls were significantly different in all four landing areas ($p < 0.05$ for all cases). Comparisons between medium and large balls remained insignificant ($p > 0.05$).

This analysis is consistent with findings of Brouwer et al. (2006) and Peper et al. (1994). Balls undergoing the same trajectory were perceived to land in different locations, or undergo different 3-D directions of motion, as a function of their absolute image size. Given the results from this experiment, which show that the different absolute ball sizes used for Experiment 1 could have affected our results, further study must be conducted to resolve the real cause for the observed changing-size cue effects. This question is addressed in Chapter 5.

4.3 Experiment 3: Static reference frame

Two previous studies indicated that a static reference frame is not essential for solving ball-catching tasks (Saxberg 1987b; Oudejans et al. 1999). In theory, the final landing site can be determined without information about a static reference frame (Saxberg 1987a; Regan and Kaushal 1993). In the virtual ball-catching task we created, a static floor grid may serve as a reference frame for perspective projection that shows an explicit ground plane where the ball is launched, and where the ball is expected to land. The reference frame may also provide a depth cue as grid squares that are far away from the viewer appear smaller than those close to the viewer. This cue may aide viewers in predicting the ball's location in depth. With these observations in mind, we hypothesize that without the floor grid, the location of the ground plane may be less clear, leading to greater uncertainty in depth about when the ball will land.

4.3.1 Methods

The static reference frame in this experimental setup appears as a background floor grid (Figure 1A). The experimental setup follows that of the general methods. The subjects viewed small and large (0.15m and 0.25m) balls following a complete trajectory for the first training condition and a 95% trajectory for the second training condition. In both training conditions, the background floor grid was shown. For the experimental condition, subjects viewed the first 95% of a trajectory with small and large balls randomly interleaved without the static floor grid. There were an equal number of small and large balls presented.

4.3.2 Results and Discussion

Subjects reported feeling “lost” upon seeing the ball undergo a trajectory without a background grid. The three-dimensionality of the setup appears degraded without the background grid following the horizon. These subjective impressions, however, were not reflective of subjects’ performance.

The results were consistent with those of previous studies. The static reference frame did not have significant effects on the subjects’ landing site predictions in the depth direction. We conducted a single-factor ANOVA for data that were pooled for the four landing areas and four subjects. One subject was removed from data analysis to maintain equal variances. For both ball sizes that we tested, the depth errors between the setup with the static reference frame and those obtained without the static reference frame were not significantly different ($p > 0.05$, Figure 14). Consistent with findings from Experiment 2, small balls (0.15m) were predicted to land farther away from their true landing sites. Large balls (0.25m) were predicted to land closer to the viewer compared to their true landing sites (Figure 14). When analyzed using angular direction of motion, and separating the four landing areas, no significant differences between the frame and no frame experiments were observed ($p > 0.05$).

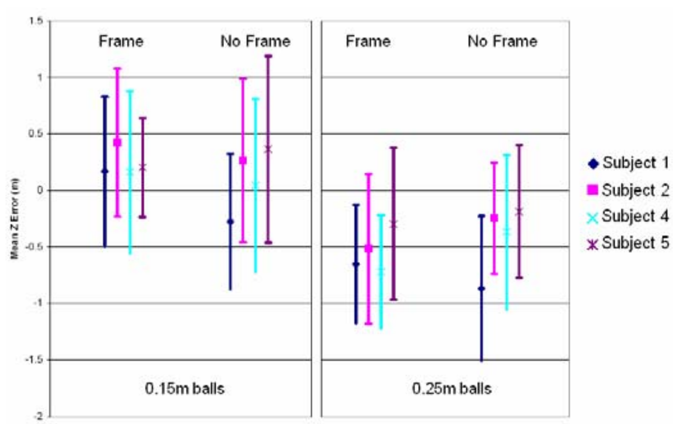


Figure 14. Mean depth errors showing standard deviations in meters for the four subjects with and without the static reference frame for small and large balls.

Though the findings in this experiment are consistent with those from previous studies, it should be noted that this experiment was conducted in the second session with the subjects. By the time this experiment was conducted, subjects had already performed more than 300 catches with the background reference frame and may have already been accustomed to the ground plane. Subjects may not have used the background reference frame cue to their full advantage, relying instead on prior expectations of the ball's location in space. By the second session, subjects' training performance had greatly improved (Figure 6). Further study with naïve subjects would better confirm the validity of our results.

4.4 Experiment 4A: Portion of trajectory viewed

Information about the initial 3-D position and velocity of a ball undergoing a free-fall trajectory can be derived from the early portion of the image trajectory (Saxberg 1987a; Brouwer et al. 2006; Todd 1981). Saxberg's theoretical investigation (1987a) demonstrated the use of image position and motion over time using the variable filter and least-squares methods to determine initial 3-D conditions of a moving object. Although the initial launch point and velocity could be obtained from viewing any portion of the trajectory including a short initial segment, computer simulations showed that the accuracy of these calculated values increased as more of the trajectory was integrated over time.

McLeod and Dienes (1996) found that outfielders run towards the direction of a ball's eventual landing site within 500ms of its launch. Their study also demonstrated that although outfielders initiate correct movement early in the trajectory, outfielders' movement during the rest of the ball flight suggests that they do not know the actual landing site until moments before the ball arrives. Brouwer et al. (2006) showed that while viewing only the first 319ms of a fly ball, subjects' landing site predictions were correlated with angular velocity as the trajectory evolves. Todd's theoretical study (1981) showed that enough information can be extrapolated from the location of the peak of the ball's trajectory to determine whether the ball will land in front or behind the viewer. Seeing the peak of the trajectory could also serve as a time cue for subjects – the time it takes for the ball to arrive at the peak of the trajectory is the same amount of time it takes the ball to hit the ground. Todd's perceptual experiments showed, however, that subjects do not take advantage of the information available at the peak of the trajectory, as subjects committed the same errors in experiments where the trajectory was shown with or without the peak.

Incorporating all of these findings, Experiment 4 presented trials where the viewer saw 95%, 65% and 45% of the same trajectories. Comparison between the 65% and 45% landing site data should show the catching behavior differences with and without the peak of the trajectory. After 95% of the trajectory is shown, the remaining portion of the ball flight follows an approximately linear slope to arrive at the landing site. At that point, prediction of the landing site should become much easier, as the observer can just extrapolate the linear path of the ball to the ground. This could lead to reduced error evident in the landing site predictions for the 95% trajectory conditions.

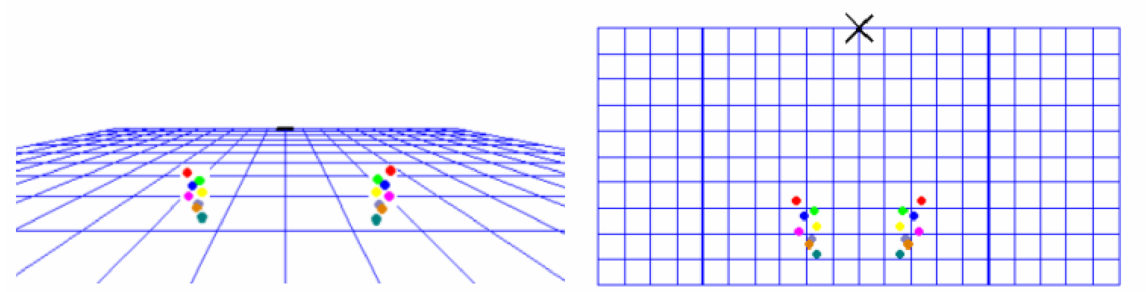
If subjects' performance is not degraded with shorter trajectories, then this would suggest that the limited visual cues available in the initial trajectory segment, such as the initial direction, velocity and acceleration of the ball in the image, are adequate to perform the task. If subjects' performance is degraded, then we should examine the type of degradation, bias or uncertainty, and investigate which cues are available when the threshold for degradation is reached.

Aside from examining the use of cues available in the early portion of the trajectory, this experiment also allows us to investigate whether subjects predict the ball's eventual landing site or merely track the ball's projection on the ground plane (Figures 1A and 3). McLeod and Dienes (1996) and Peper et al. (1994) suggest that subjects do not know the ball's eventual landing site at the outset of its flight. In McLeod and Dienes (1996), subjects did not arrive at the ball's landing site until moments before the ball landed, and in Peper et al. (1994), subjects did not complete their reach for the ball until the ball crossed their body's frontal plane. These studies suggest that subjects relied on continuously tracking the ball's movement over time to make adjustments until the ball arrived, instead of predicting the ball's eventual arrival site early in the trajectory. We investigated this issue by examining our subjects' mouse track data.

4.4.1 Methods

This experiment was conducted in the third and fourth sessions of this investigation (Table 1). Both sessions began with the 100% and 95% training conditions. In the third session, the experimental condition consisted of viewing 65% of the trajectory. The fourth session, conducted two weeks later, consisted of viewing 45% of the trajectory in the experimental condition. All trials within an experimental condition showed the same portion of the trajectory.

In both training and experimental conditions, the four ball landing areas were replaced with 16 fixed landing points (Figure 15). This allowed us to compare more directly, the performance for predicting a particular landing site given different portions of the same trajectory. In each session, there were a total of 288 trials: 6 trials were conducted for each of the 16 landing points for the two training conditions and the experimental condition.



(A) (B)

Figure 15. Image view (A) and birds'-eye view (B) of 16 landing sites for the ball undergoing a free-fall trajectory in Experiments 4A and 4B.

Before the experimental conditions were tested, subjects were told how much of the trajectory would be shown. Subjects were instructed to move their mouse palette to the ball's eventual landing site and click the mouse at the point where they believe the ball would land.

4.4.2 Results and Discussion

Subjects felt a lack of confidence when performing the task, which they attributed to viewing only a short portion of the trajectory. Most of the subjects thought they were blindly guessing the balls' landing sites during the initial trials and found the task more difficult than preceding experimental conditions. Subject 1 claimed that she was completely guessing the landing sites with the 65% trajectory and chose to withdraw from the 45% trajectory condition. Subject 2 consciously moved the mouse much more quickly when the initial portion of the trajectory was visible and made minimal adjustments when the ball disappeared.

4.4.2.1 Analysis of landing sites

In general, landing site predictions in the horizontal direction had similar accuracy across all subjects (Figure 16A). Mean landing site prediction errors were not significantly different when data from all subjects were pooled and compared between different portions of the trajectory viewed ($p > 0.50$). In the depth direction, there were no consistent trends in the fluctuation of errors in predicted landing sites (Figure 16B). Subject 2, who had the greatest increase in uncertainty in the horizontal direction, maintained constant accuracy and precision in the depth direction. Subject 3 predicted that the balls with shorter trajectories were going to land farther away in depth, while subject 4 perceived the balls viewed with 65% and 45% trajectories to land closer in depth relative to their true landing site. There were very weak trends in overall mean error in the depth direction. Subjects 3 and 5 were less accurate in predicting the landing site in the 45% condition compared to the 65% trajectory. Their errors however, were in opposite directions.

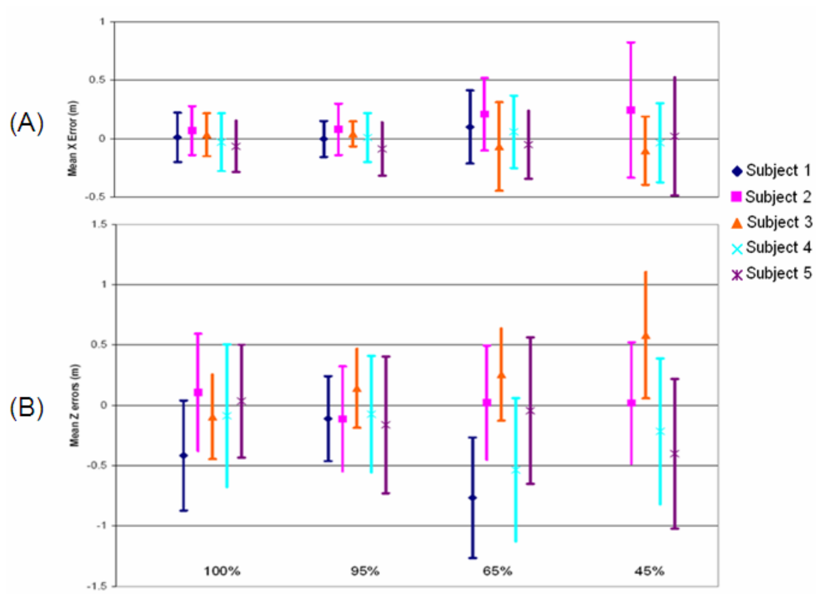


Figure 16. Mean errors showing standard deviations in the horizontal (A) and depth (B) directions with varying portions of trajectory viewed for five experimental subjects.

Variance slightly increased across all subjects in the horizontal and depth directions with shorter trajectories, with the exception of Subject 3, whose precision increased in the horizontal direction from the 65% to the 45% conditions. The increase in variance in the horizontal direction from 95% to 45% was significant when all of the subjects' standard deviations were pooled together ($p < 0.05$). The increase in variance in the horizontal direction from 95% to 65% was close to significance when subjects were pooled together ($p = 0.071$). Although the variance in the depth direction increased across all subjects as the shorter trajectories were viewed, none of the increases in variance were significant.

The minimal degradation in the accuracy and precision of eventual landing site predictions suggests that subjects are able to extract valuable information from the early portions of the trajectory. This is despite the subjective impressions of the difficulty of this task. The lack of a systematic shift of means across subjects suggests that individual subjects may use cues such as the location or time of the peak, or the final linear segment of the downward trajectory, to varying degrees. While Subject 3 showed a constant increase in mean error and variance in the depth direction with shorter trajectories, Subject 2's performance across the different portions of trajectory viewed has similar accuracy and precision. This suggests that the peak of the trajectory and the final linear segment of the downward trajectory may be important visual cues to Subject 3, but not to Subject 2. Analysis of individual subjects' mouse tracks may provide further insight into the different strategies subjects may have employed.

4.4.2.2 Analysis of mouse tracks

As suggested earlier, individual subjects may use different strategies for solving this task. Analysis of subjects' mouse tracks may give valuable insight into the catching behavior when different portions of the trajectory are viewed. Subjects whose performance varied greatly with the portion of the trajectory viewed may be tracking the ball as it moves, making small but accurate adjustments as more information is provided. This could explain the systematic bias in some of the subjects' landing site predictions. Subjects whose performance was unaffected by the portion of the trajectory viewed may be predicting landing sites early in the trajectory, possibly employing cues other than the peak of the trajectory.

We observed these two distinct behaviors within the five subjects. We classified the subjects as 'trackers' or 'predictors' according to their mouse tracks (Figure 17A and B). Figures 17 A and B show Subject 4 and Subject 1's mouse tracks for all 6 trials going to one landing site, which are representative of the trackers and predictors groups respectively. There were three trackers who moved the mouse diagonally in the image and in depth following the ball's projected movement on the ground plane (Figure 17 IA). The birds'-eye view of the mouse tracks reveal that the subjects moved the mouse almost directly below the ball's trajectory as it evolved over time (Figure 17 IIA). Tracking velocity was also very close to the ball's velocity (Figure 17 IIIA).

The two predictors followed a circuitous path towards the ball's landing site (Figure 17 IB). Predictors moved the mouse rapidly in depth then gradually adjusted in the horizontal direction in a tracking manner (Figure 17 IIB). The initial movement in depth brought Subject 1's mouse very close to the ball's eventual landing site, but the subject consistently took almost four times as long to move through the same amount of 3-D distance to goal in the horizontal direction (Figure 17 IIIB). By the time step 10, Subject 1 moved four meters closer to the landing site, but took from time step 11 to 50 to arrive at the landing site, which was only 2 meters away. This behavior was also observed in mouse tracks of other predictors (see Appendix C).

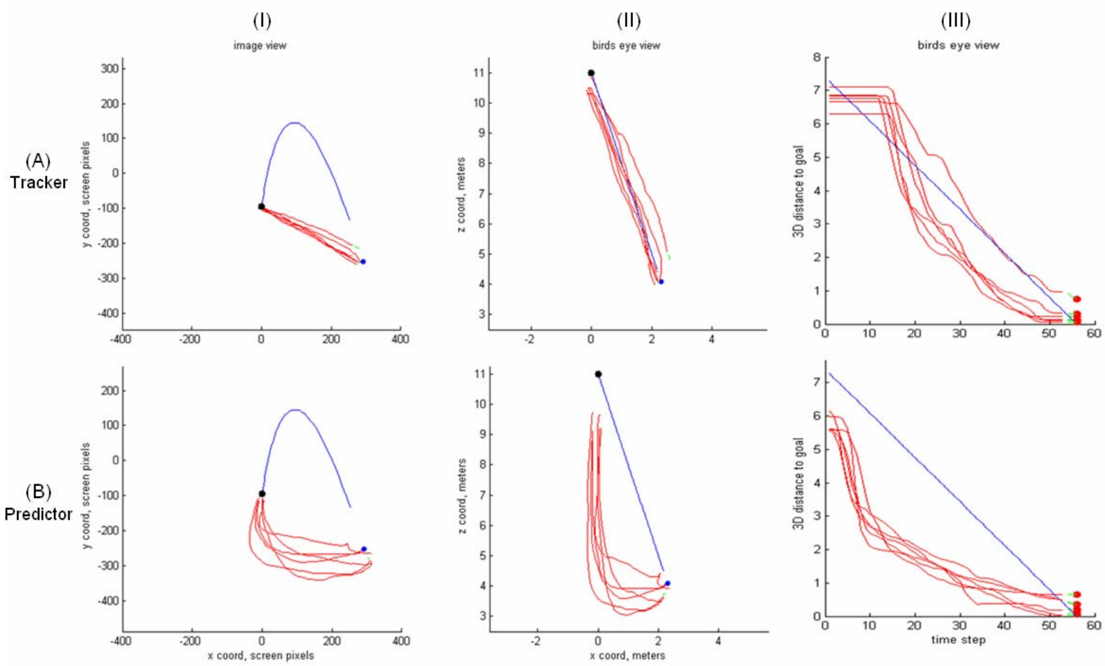


Figure 17. (A) 'Tracker' and (B) 'Predictor' (I) image view and (II) birds'-eye views of mouse tracks and (III) 3D distance to the landing site in meters through time steps for the same landing site given a 95% trajectory. The red lines show the subjects' mouse track movements in different trials while the ball is visible. The green lines show the subjects' mouse tracks after the ball has disappeared. In (I), the blue line shows the ball's visible trajectory and the blue dots show the ball's true landing site. In (II), the blue line shows the projected ground path, and in (III), the blue line shows the 3-D distance of the ball to the goal.

The tracking or predicting behaviors were observed across the different portions of trajectory viewed (Figure 18). The mouse tracks for the condition where only 65% of the trajectory was viewed clearly depict how much closer the predictor is to the true landing site compared to the tracker after a short period of time (Figures 18 IIA and IIB). The green lines indicate the subject's mouse movement after the ball disappeared. Figure 18 IB shows that after the ball disappeared, the predictor was very close to the correct landing site and made very few adjustments afterwards. The tracker followed a steady path while the ball was visible and continued on this path at a minimally-changing velocity after the ball disappeared. This strategy is consistent across all six trials for the same landing site (Figure 18 IIIA). Both the tracker and the predictor's mouse tracks show greater variability after the ball disappeared in the 65% condition compared to the 95% condition, suggesting that they continued to make small corrections as the trajectory evolved.

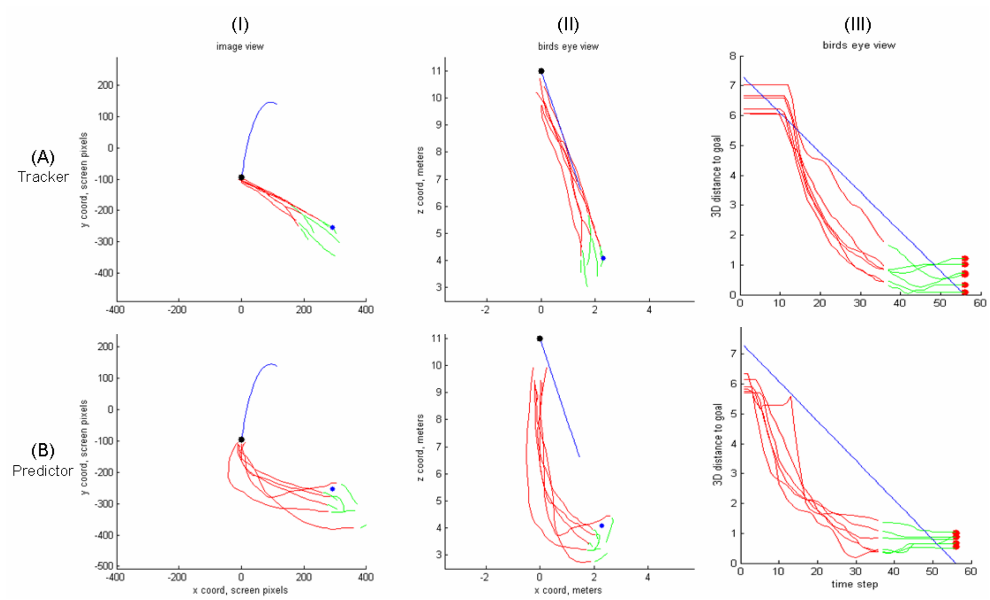


Figure 18. (A) 'Tracker' and (B) 'Predictor' (I) image view and (II) birds' eye views of mouse tracks and (III) 3D distance to the landing site in meters through time steps for the same landing site given a 65% trajectory. The red lines show the subjects' mouse track movements in different trials while the ball is visible. The green lines show the subjects' mouse tracks after the ball has disappeared. In (I), the blue line shows the ball's visible trajectory and the blue dots show the ball's true landing site. In (II), the blue line shows the projected ground path, and in (III), the blue line shows the 3-D distance of the ball to goal.

Within the group of trackers and predictors, there were subjects who consistently undershot the true landing site when only short portions of the trajectory were shown. This observation was particularly noticeable when subjects viewed 45% trajectories (Figure 19). Subject 5 tracked the ball's projection onto the ground plane as seen in the birds'-eye view of her mouse movements (Figure 19 IIA). Subject 2 was a predictor, as seen in the curvature of the birds'-eye view of her mouse tracks (Figure 19 IIB). Similar to Subject 1's performance, the predictor made significant progress towards the ball's true landing site while the ball was visible compared to the tracker. Subject 2 quickly judged the ball's landing site in the depth direction correctly, but needed to track afterwards in the horizontal direction. After the ball disappeared, Subject 2 stopped her horizontal movement. Subject 5 steadily continued on the path she had determined after the ball disappeared. In both cases, the tracker and the predictor assumed that the ball was going to land sooner than it actually did (Figure 19 IA and IB). The subjects were able to determine where in depth the ball was going to land, but both incorrectly judged the ball's location in the horizontal direction. Over-anticipation of the ball's descent, resulting in predictions short of the ball's true landing site in the horizontal direction, was more prevalent when catching balls landing on the left side, but was also observed with balls landing on the right side.

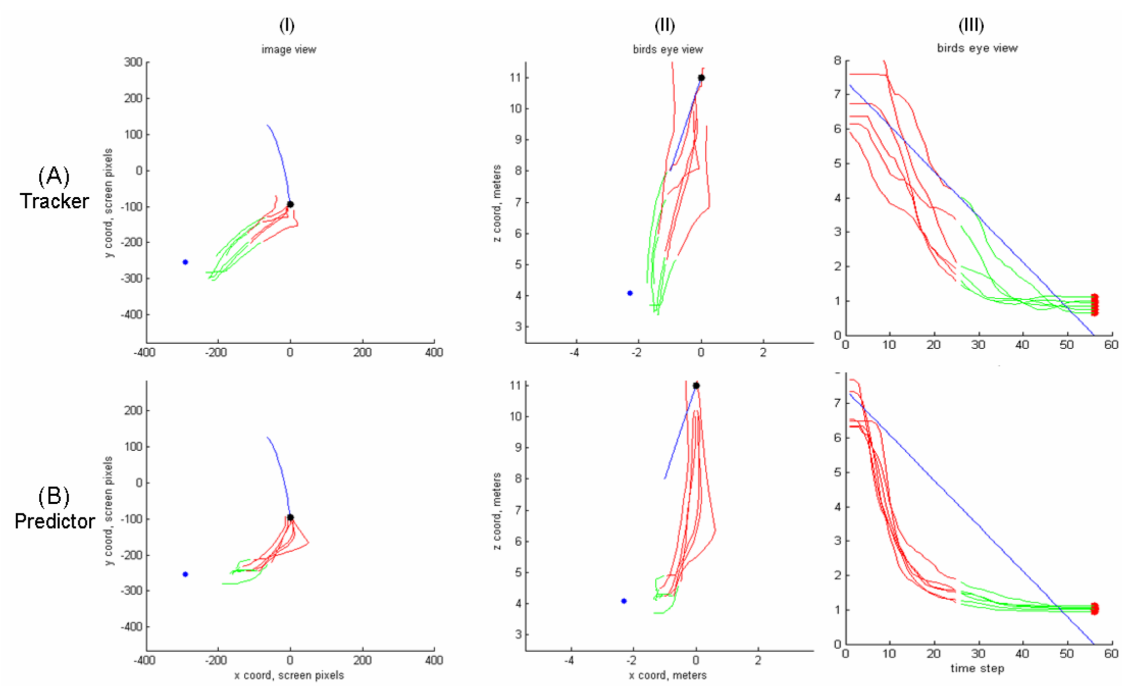


Figure 19. (A) 'Tracker' and (B) 'Predictor' (I) image view and (II) birds' eye views of mouse tracks and (III) 3D distance to the landing site in meters through time steps for the same landing site given a 45% trajectory. The red lines show the subjects' mouse track movements in different trials while the ball is visible. The green lines show the subjects' mouse tracks after the ball has disappeared. In (I), the blue line shows the ball's visible trajectory and the blue dots show the ball's true landing site. In (II), the blue line shows the projected ground path, and in (III), the blue line shows the 3-D distance of the ball to goal.

The distinction between two different catching strategies was also apparent in an additional experiment we conducted where the catching palette was moved to the center of the ground plane.

4.4.3 Experiment 4B: Portion of trajectory viewed with the catching palette starting at the center

McLeod and Dienes (1996) reported that outfielders initiated movement in the correct direction, forward or backward, towards a ball's eventual landing site within 500ms of its launch. In this experiment, we moved the catching palette to a central location in depth that was roughly the mean of the depths of the 16 true landing sites. In this case, a correct prediction of the landing site requires forward movement of the palette for some trajectories and backward movement for others. We sought to determine subjects' initial impressions of the ball's eventual landing site from their early mouse track data.

4.4.3.1 Methods

The experimental setup followed that of Experiment 4A, where there were two sessions that tested landing site predictions with the 65% trajectory in the first and the 45% trajectory in the second. The catching palette was moved 7m closer to the viewer to appear 4m instead of 11m away from the viewer. The sessions were three weeks apart.

4.4.3.2 Results and discussion

With this simple change in the experimental setup, a few of the subjects reported that they felt slightly disoriented. Subject 4, who was a tracker in the previous experiment, sensed that her predictions were less accurate when trying to intercept the ball directly at its landing site. After a few trials using this strategy, the subject resorted to her earlier tracking strategy by moving the palette towards the ball as soon as the ball was launched and tracked the ball's projection on the ground plane (Figure 20 IA).

Subject 1, the predictor in Experiment 4A, reported that this task was easier compared to the earlier experiment. Because the catching palette was positioned closer to the landing sites in the depth direction, Subject 1's initial movement was in the horizontal direction, directly towards the ball's landing site, as the ball approached (Figure 20 IB).

The movement over time of the tracker and the predictor seems to follow a different pattern compared to Experiment 4A. With the catching palette starting from a central location in depth, the predictor's 3-D distance to goal was constant, suggesting a roughly circular arc around the landing site initially (Figure 20 IIIB). By moving away from the landing site towards the path of the approaching ball, the tracker did not make any improvements in the distance to the landing site until later in the trial (Figure 20 IIIB).

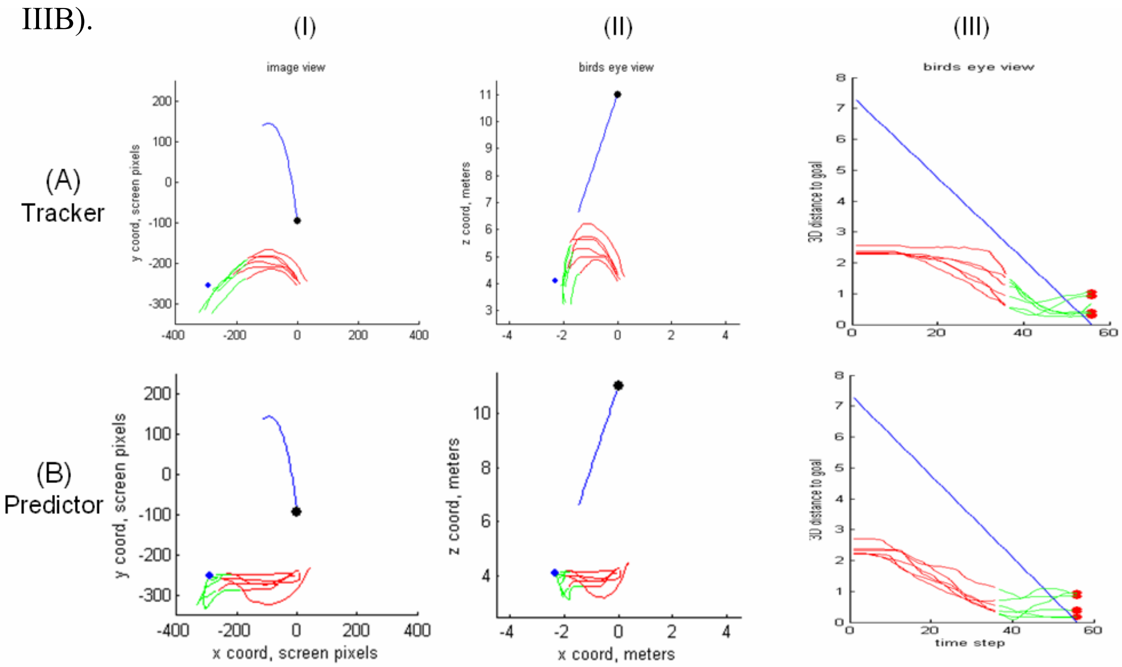


Figure 20. (A) 'Tracker' and (B) 'Predictor' (I) image view and (II) birds' eye views of mouse tracks and (III) 3D distance to the landing site in meters through time steps for the same landing site given a 45% trajectory, with the catching palette positioned in the center of the landing sites. The red lines show the subjects' mouse track movements in different trials while the ball is visible. The green lines show the subjects' mouse tracks after the ball has disappeared. The blue lines show the ball's visible trajectory and the blue dots show the ball's true landing site.

From the initial segment of the trajectory, the trackers seemed to get a good sense of the projection of the 3-D direction and speed of motion of the ball on the ground plane, and were able to initiate fairly accurate tracking movements that follow this path. There was a delay of about 330ms before the tracking behavior started but the trackers quickly moved to a point along the ground path that was slightly ahead of the ball's current position, and followed this path with a velocity of movement that was similar to the ball's projected velocity. When they viewed only 45% of the trajectory, they were still able to initiate appropriate tracking behavior, and they maintained a roughly constant direction and speed of movement after the ball disappeared. They were not able to make further corrections after the ball disappeared, resulting in slightly greater variability in their mouse tracks during the final approach, but they did seem to have a good sense of when (or where) the ball would have hit the ground, as their final landing site predictions had similar accuracy to those obtained with longer trajectories. The predictors may focus more on using the visual cues in the initial segment to determine the movement of the ball in depth, (we know, for example, that the changing size cue can directly indicate relative movement in depth), and later focus on cues to the horizontal movement of the ball, such as the direct use of the horizontal movement in the image.

The strong tendency to follow either the tracking or the predicting strategies gives a relevant insight into different approaches for solving the same task. Considering the homogeneity of subjects' landing site predictions when viewing a complete 100% trajectory (Figure 16), we can clearly show that there are different approaches to arrive at the same landing site prediction.

Chapter 5. General Discussion and Further Studies

This thesis investigated three visual cues that are available to viewers of a 2-D image projection of a ball undergoing a parabolic 3-D trajectory. We investigated the changing-size, absolute ball size and static reference frame cues, which have been investigated in the past both theoretically and perceptually, but never by the same investigator using the same experimental setup. The setup that this investigation used was based on an earlier study (Saxberg 1987b), which allowed for the manipulation of several visual cues in a computer simulation.

As predicted, Experiment 1 showed that enhancing the changing-size cue led to the perception that the ball was moving in a direction closer to the viewer and with greater movement in depth. Reducing the rate of change of the image size of the ball had the opposite effect. This behavior could be the consequence of a correlation between the rate of change of image size and the absolute image size of the ball in our first experiment. This explanation was tested in the second experiment, which demonstrated a systematic bias depending on a ball's absolute size when the changing-size cue was removed. Small balls were perceived to land farther away, while large balls were perceived to land closer to the viewer, relative to the ball's true landing site.

The static reference frame did not affect subjects' perceptions of the ball's eventual landing site in both accuracy and precision. It is possible that the subjects' significant training before this experimental condition allowed subjects to become accustomed to the 3-D trajectory regardless of the static reference frame cue. Subjects may have also developed an expectation for the location of the ground plane that can be used in the computation of the landing site, similar to the use of a visible ground plane. Further study with naïve subjects would validate the results from this experiment.

Experiment 4, where the portion of trajectory viewed was varied, did not show any systematic errors in accuracy and precision within the five subjects. Analysis of individual mouse tracks, however, suggested that different subjects use different strategies to solve the ball-catching task. Three subjects adapted a tracking strategy and followed the ball's projection on the ground as the trajectory evolved. Two subjects adapted a predictive strategy and moved the catching palette rapidly in the depth direction towards the ball's eventual landing area, then tracked in the horizontal direction for the remaining part of the trajectory. Within the trackers and predictors groups, there were two subjects who consistently judged the landing site to be further from the true landing site in the horizontal direction. The subjects' mouse movements stopped shortly after the ball disappeared. This behavior accounted for the bias in these two subjects' landing site predictions.

There are other issues that analysis of the mouse tracks revealed, which need to be addressed when drawing conclusions from this experimental setup. One is whether subjects' tracking or predicting behavior changed depending on the portion of the trajectory they expected to view. Because subjects were explicitly told what portion of the trajectory they would view, and saw the same portion of the trajectory for all trials within an experimental condition, subjects may have consciously extrapolated more information from the initial portion of the trajectory in short conditions compared to when they were aware that they would view the entire trajectory. We conducted a preliminary experiment testing one subject's behavior when short and complete trajectories were randomly combined in one experimental condition. The results show that the subject behaved differently depending on the portion of the trajectory she expected to view. The subject behaved consistently when the 95%, 65% and 45% trajectories were randomized in one experimental condition, but behaved differently when the different portions of the trajectory were separated in different conditions.

Another issue to address further is the general discordance of visual perception and motor movement. Oudejans et al. (1997) demonstrated that expert and non-expert outfielders have the same perceptual predictions on where launched balls will land; however, in a catching condition, where expert and non-experts had to initiate movement to retrieve the ball, experts fared better than non-experts. In our experiment, all of our subjects were athletes or video-game players. We assumed that subjects who assert better-than-average visuo-motor skills can manifest their perceptual judgments in their motor behavior in these experimental conditions. Future experiments could examine the performance of subjects with a broader range of motor skills, and correlate performance in this task with other tests of motor skill.

In future experiments, it would be valuable to track subjects' eye movements during the trials. In this study, we controlled the visual stimulus available on the computer monitor, but allowed subjects to make free eye movements. Tracking the eye movements made during each trial would allow us to determine the exact nature of the visual image on the retina, which can then be correlated more closely with motor behavior. The subjects' eye tracking behavior can also provide insight into their strategy for solving this task. For example, if subjects look at particular locations, such as the peak of the trajectory or the final landing site, or track the ball with their eyes, it might suggest that these cues are particularly important when performing this task.

A computer simulation with an environment viewed in stereo could also be considered in future studies. In our experiments, the display was viewed monocularly to enhance the three-dimensionality of the flat image on the screen. To create a richer 3-D simulation of the catching task, a stereo component could be added. This would allow 3-D cues, such as the trajectory of the ball's movement in depth, to better reflect what we see in natural scenes.

The subjective classification of trackers and predictors also needs to be better quantified. A control experiment where two dots are shown in succession and subjects move the mouse from the initial launch point to the final landing site would show individual motor behaviors given the same simple visual input. This will allow for the analysis of the motor component of behavior for our particular setup. This control experiment would also allow us to separate aspects of performance that are due to motor limitations versus perceptual inferences, which would be valuable in analyzing mouse tracks with different portions of trajectory viewed.

The computer simulation we created allowed us to vary many factors in the moving trajectory such as the initial launch point, size and speed of the ball, the locations of the landing sites, the gravity constant and the visual texture and layout of the 3-D environment. We have manipulated some of these factors in our experiments, but could vary more of them in different combinations in the future, while keeping our experimental variable the only parameter constant, to further validate our results and to evaluate other visual cues that influence performance in this virtual ball-catching task.

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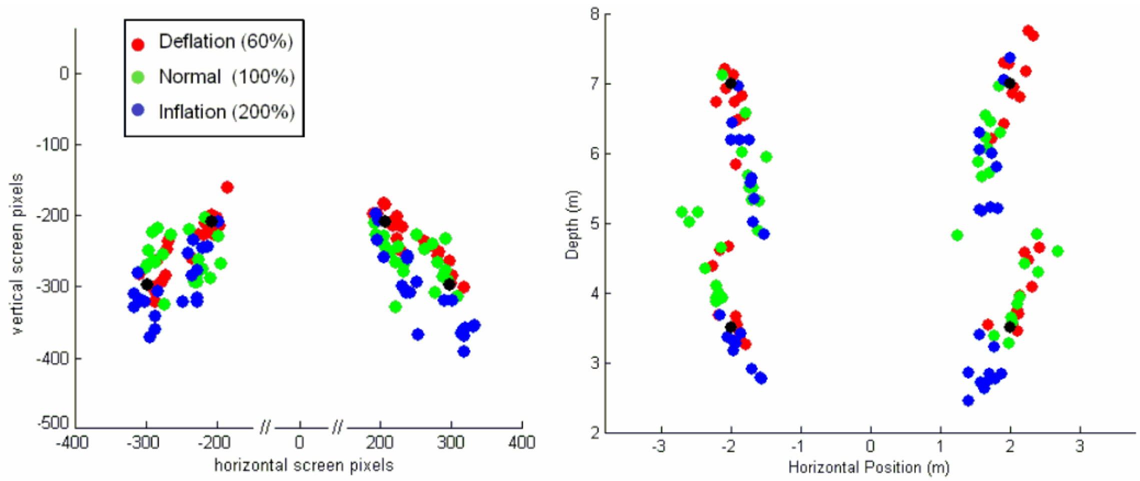
Appendix A

Image view and birds'-eye view of subjects' landing site predictions classified within the four predetermined landing sites during the changing-size cue experiment.



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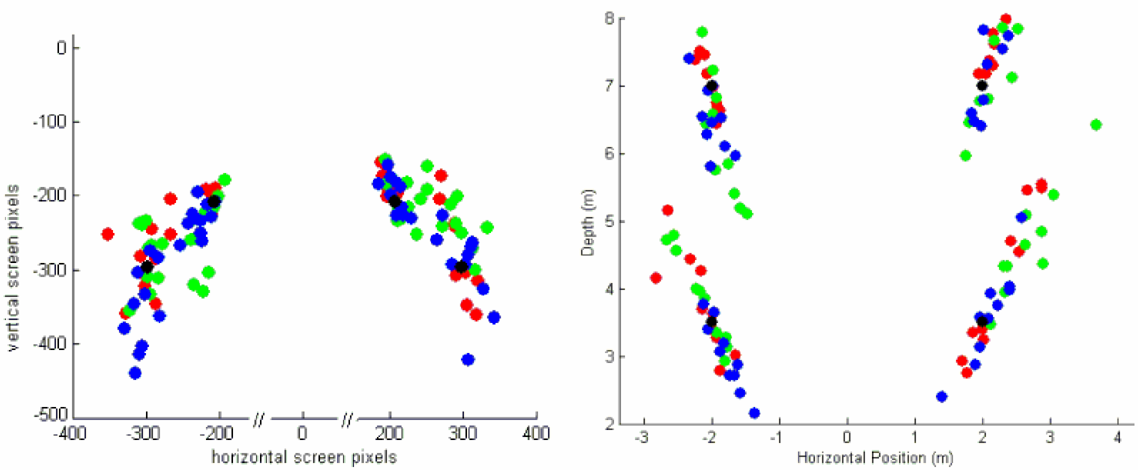

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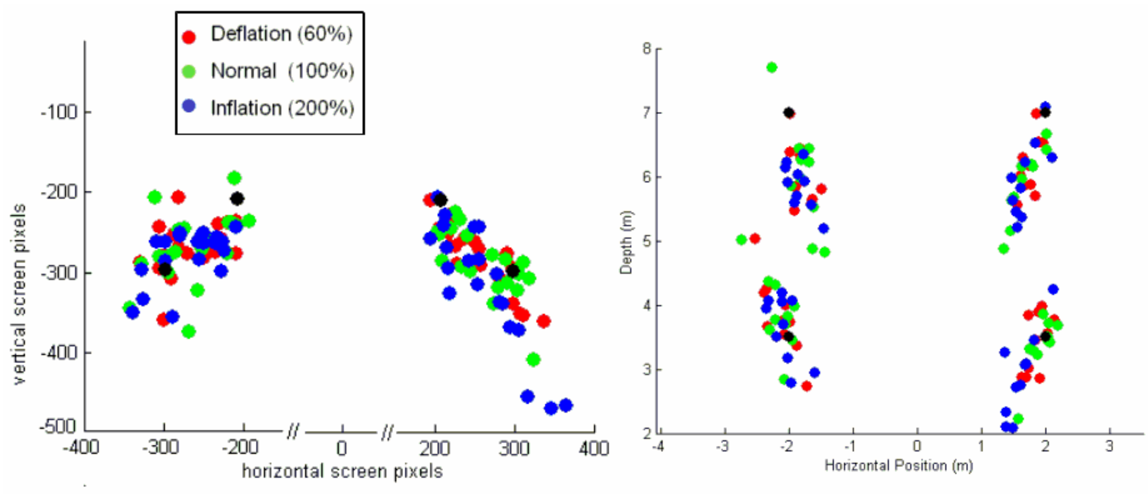

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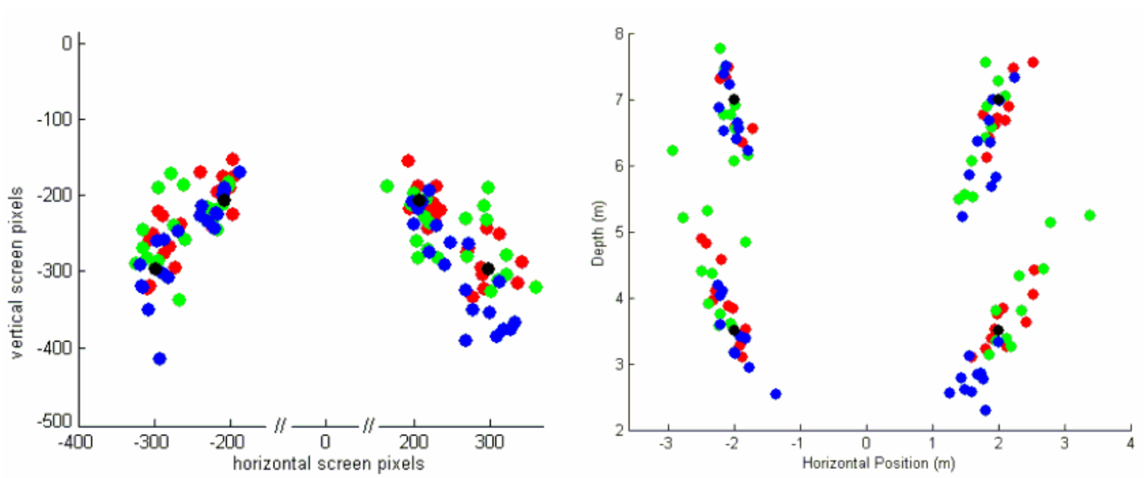
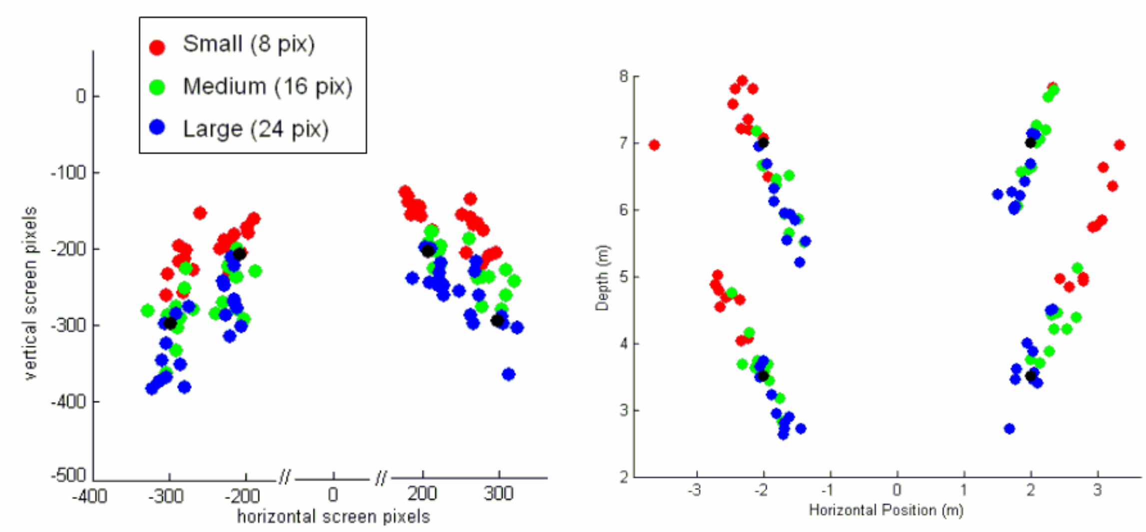


Subject 5

Appendix B

Image view and birds'-eye view of subjects' landing site predictions classified within the four predetermined landing sites during the absolute ball size cue experiment.



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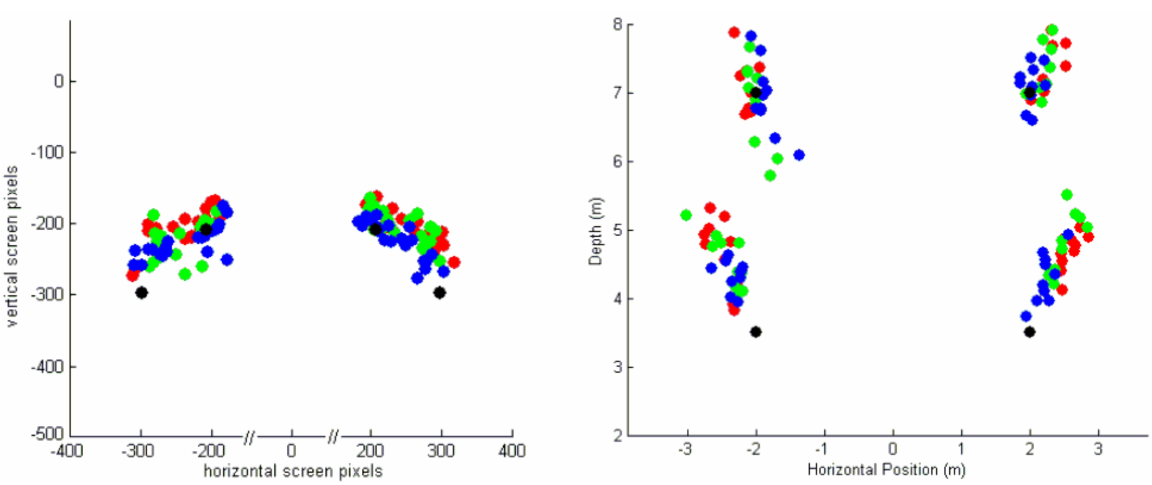

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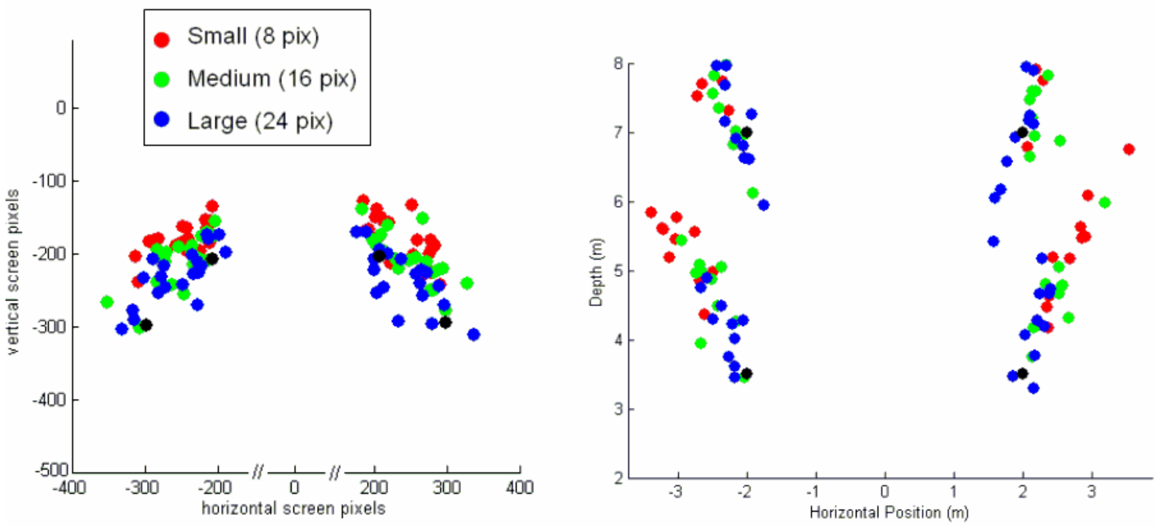

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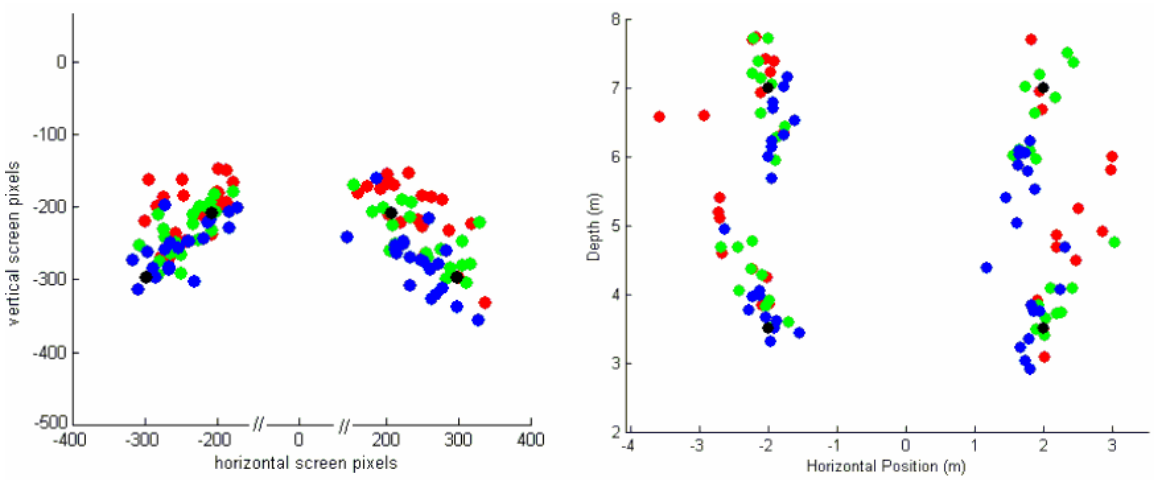
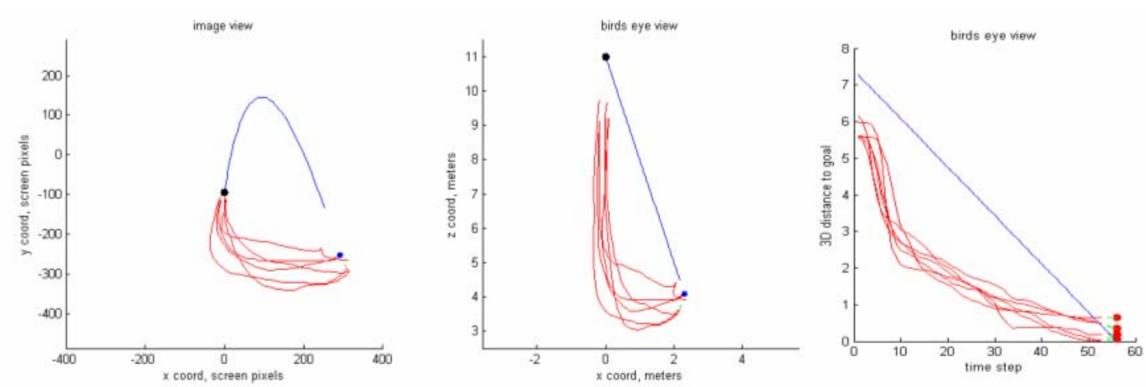


Subject 5

Appendix C

Predictors' image view and birds' eye views of mouse tracks and 3D distance to the landing site in meters through time steps for the same landing site given a 95% trajectory. The red lines show the subjects' mouse track movements in different trials while the ball is visible. The green lines show the subjects' mouse tracks after the ball has disappeared. The blue lines show the ball's visible trajectory and the blue dots show the ball's true landing site.



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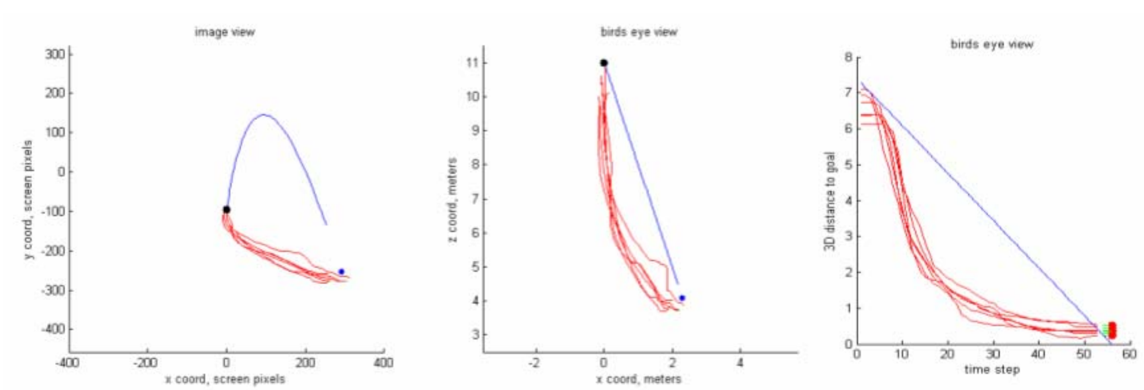
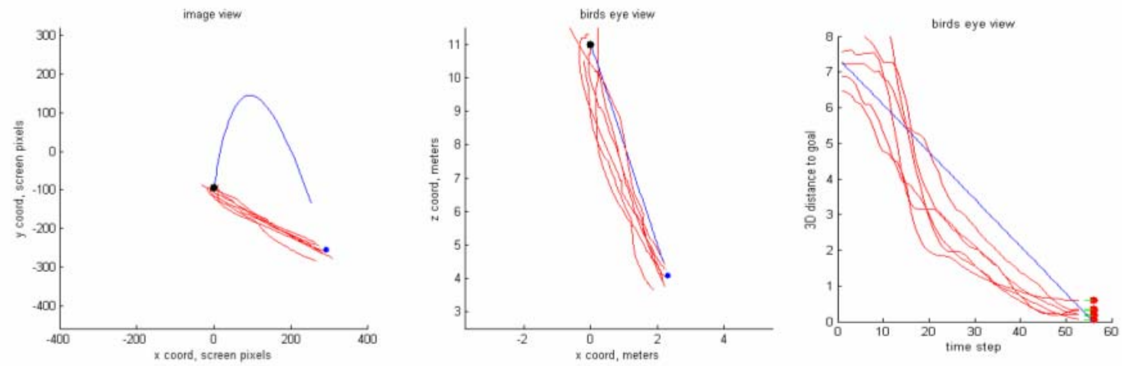


Subject 2

Trackers' image view and birds' eye views of mouse tracks and 3D distance to the landing site in meters through time steps for the same landing site given a 95% trajectory. The red lines show the subjects' mouse track movements in different trials while the ball is visible. The green lines show the subjects' mouse tracks after the ball has disappeared. The blue lines show the ball's visible trajectory and the blue dots show the ball's true landing site.



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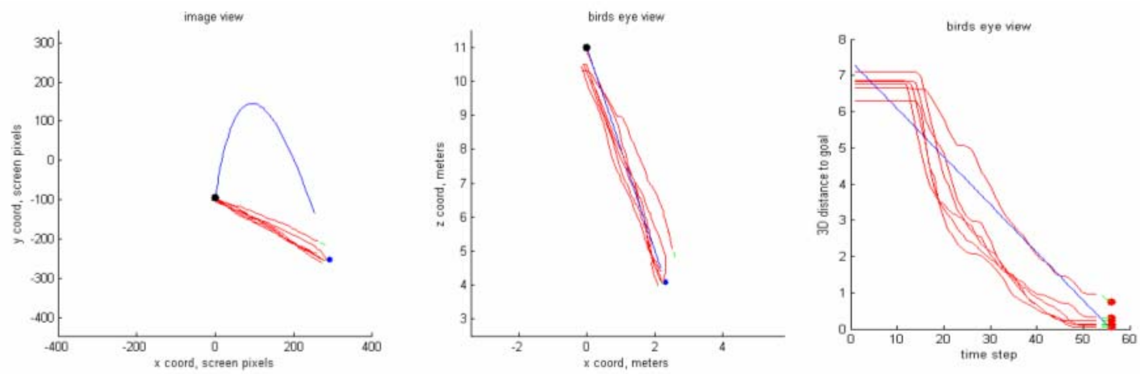

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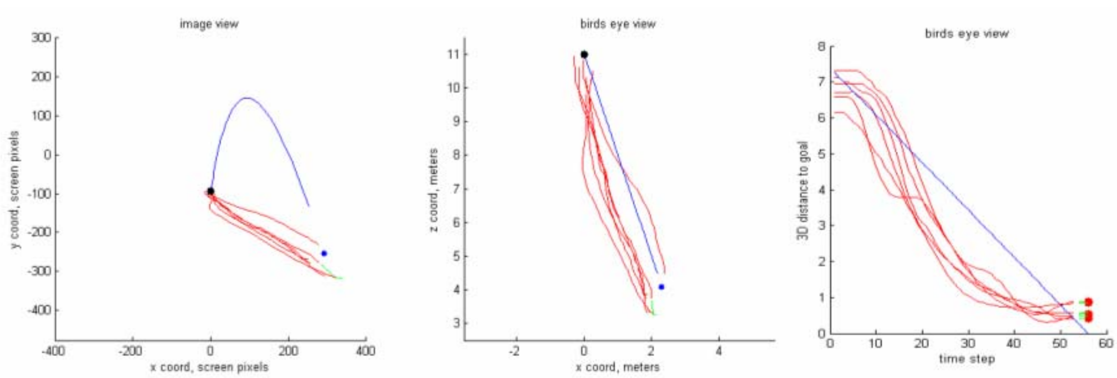
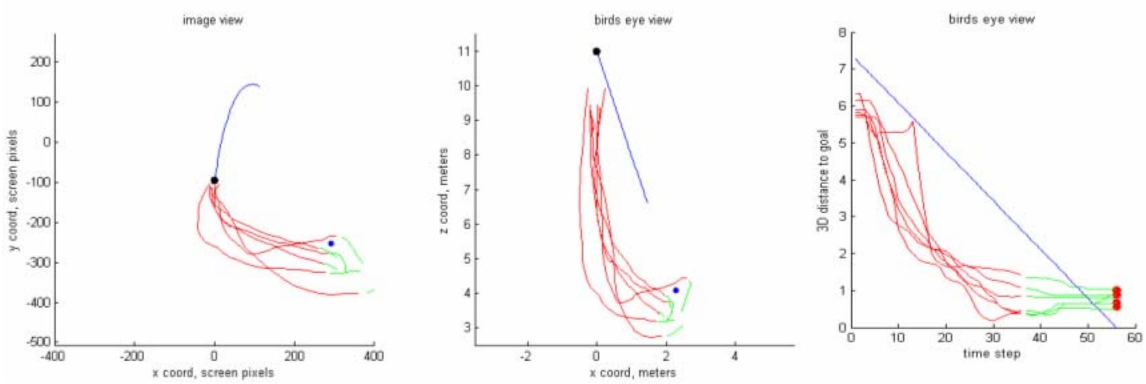


Subject 5

Predictors' image view and birds' eye views of mouse tracks and 3D distance to the landing site in meters through time steps for the same landing site given a 65% trajectory. The red lines show the subjects' mouse track movements in different trials while the ball is visible. The green lines show the subjects' mouse tracks after the ball has disappeared. The blue lines show the ball's visible trajectory and the blue dots show the ball's true landing site.



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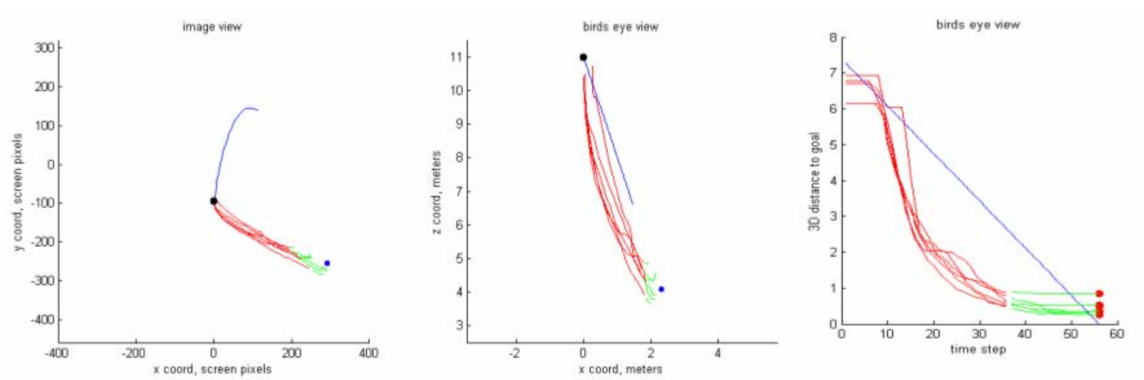

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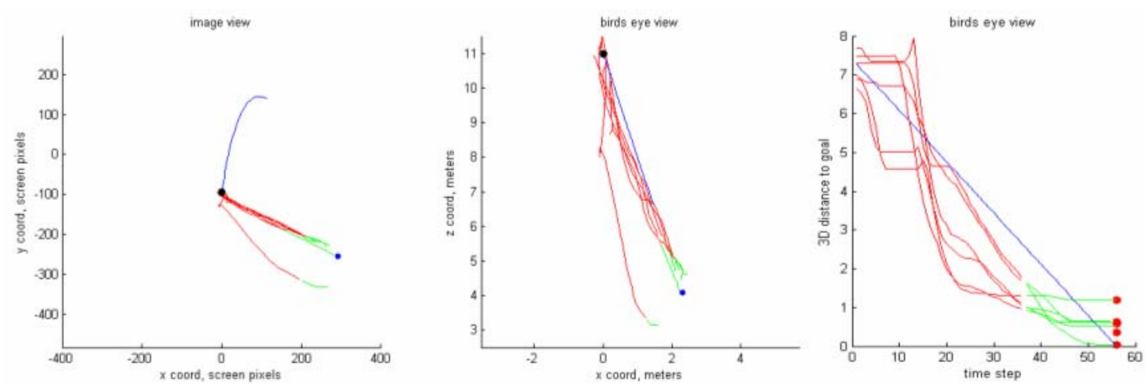
Trackers' image view and birds' eye views of mouse tracks and 3D distance to the landing site in meters through time steps for the same landing site given a 65% trajectory. The red lines show the subjects' mouse track movements in different trials while the ball is visible. The green lines show the subjects' mouse tracks after the ball has disappeared. The blue lines show the ball's visible trajectory and the blue dots show the ball's true landing site.



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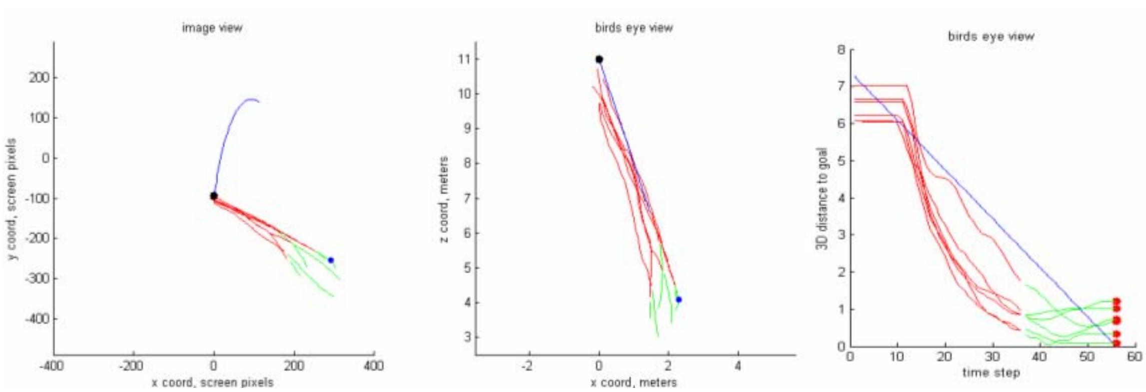

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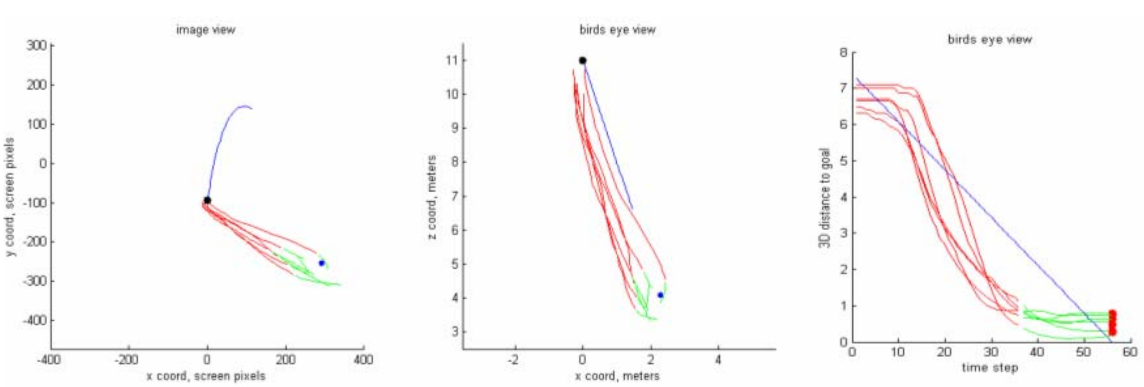
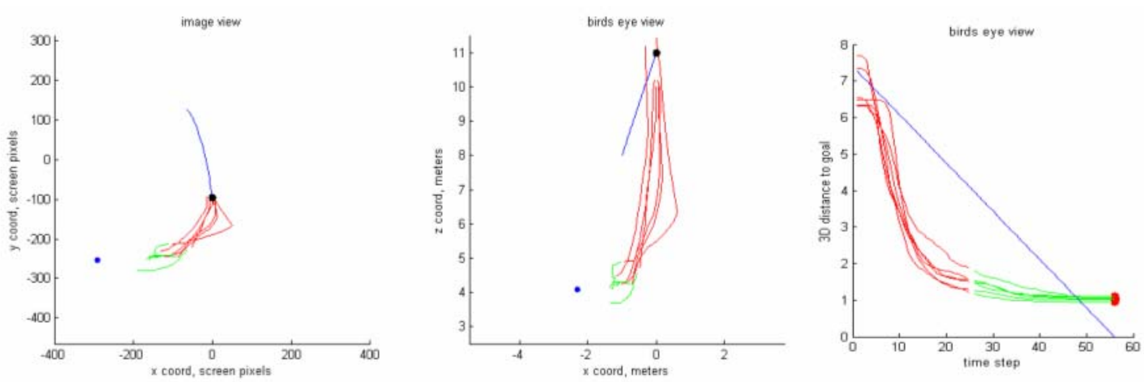


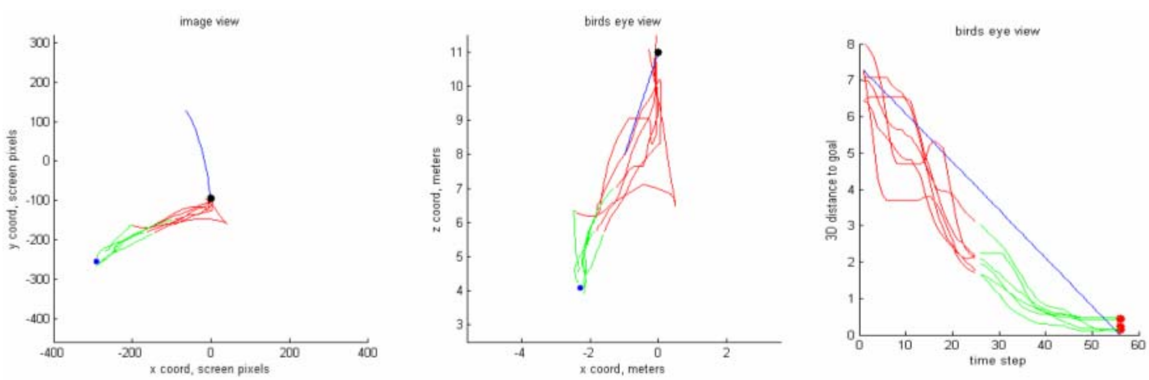
Subject 5

Predictors' image view and birds' eye views of mouse tracks and 3D distance to the landing site in meters through time steps for the same landing site given a 45% trajectory. The red lines show the subjects' mouse track movements in different trials while the ball is visible. The green lines show the subjects' mouse tracks after the ball has disappeared. The blue lines show the ball's visible trajectory and the blue dots show the ball's true landing site.



Subject 2

Trackers' image view and birds' eye views of mouse tracks and 3D distance to the landing site in meters through time steps for the same landing site given a 45% trajectory. The red lines show the subjects' mouse track movements in different trials while the ball is visible. The green lines show the subjects' mouse tracks after the ball has disappeared. The blue lines show the ball's visible trajectory and the blue dots show the ball's true landing site.



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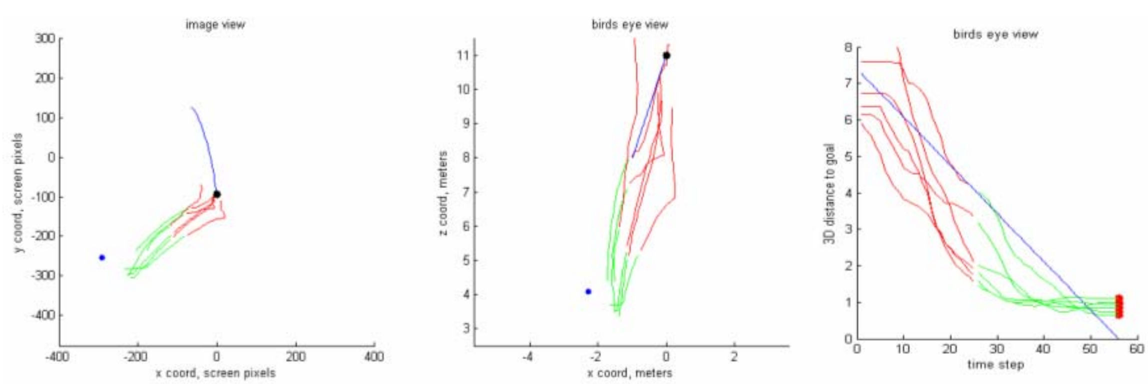

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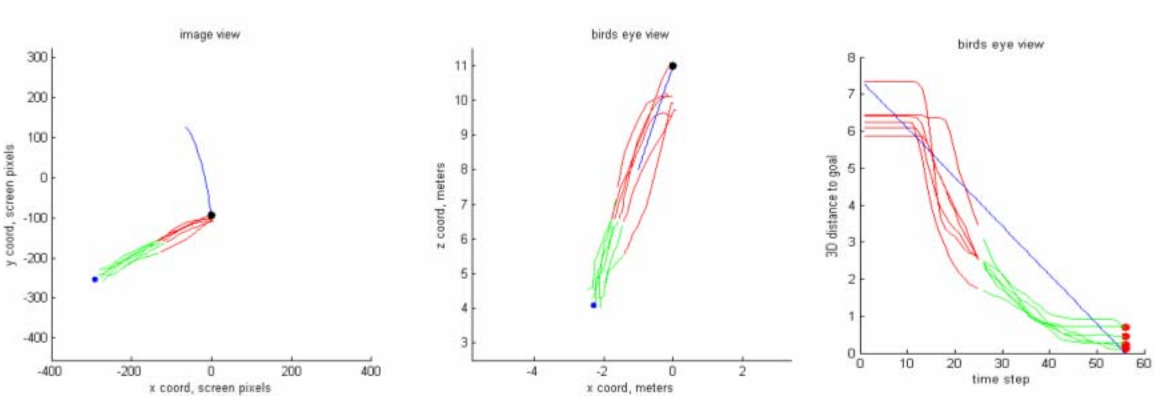

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