THE INFLUENCE OF UNCERTAINTY AND URGENCY ON VISUOMOTOR DECISION MAKING

By

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ABSTRACT OF THE DISSERTATION

The influence of uncertainty and urgency on visuomotor decision-making

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Visuomotor decision making was investigated using a virtual shooting paradigm where subjects controlled a 'gun' with a computer mouse. Subjects had a limited amount of time to choose and fire at a target among two options that varied in size and motion complexity. Results show that internal estimates of motor performance, conditioned on visual information and urgency, are used in deciding between options in a timed visuomotor task. Subjects tended to split their time between deciding and aiming in a way that brought their performance close to models that maximized expected probability of a hit and minimized shooting error. In addition, urgency led to the use of a heuristic, namely shooting at the larger target, which simplified the decision process without having too detrimental an effect on the overall task goal; hitting a target on every trial. The present study provides a platform to find out how capacities are put to use in demanding active visuomotor task environments.

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1. Introduction

The world is full of options with uncertain outcomes. Vision is often called upon to aid in selecting amongst these options in order to plan a goal-directed action. However, the process of selection takes time and the value of each option often changes over time. In addition, there is often a fixed amount of time available to achieve a goal, meaning that taking longer to decide which action is best, results in rushing the action. Uncertainty and temporal change are two obstacles that present unique problems for the decider. Uncertainty requires that they bring to bear prior information, either from experience with similar tasks or knowledge about the world in order to evaluate a set of options. Temporal change and time limits require a sensitivity to the tradeoff between the benefits of reducing visual uncertainty and the costs of rushing the selected action.

For example, when driving on a highway, changing into the left or right lane from the middle lane requires the driver to evaluate both opportunities along multiple dimensions (e.g. size of the opening in between cars, how erratic the surrounding drivers are, etc.). These different characteristics (size of lane opening and driver variability) must be combined in some way to decide which option is best. But while evaluating the two options the openings between cars may begin to shrink, tempting the driver to rush into the lane before it is too late. This may lead to an accident. However if the driver immediately picks a lane at random, they may end up in front of an unskilled driver that is likely to cause a collision.

These issues have previously been investigated to varying extents, mostly in isolation of one another. First, this review will examine work by Battaglia & Schrater (2007) that focused on the tradeoff between time devoted to visual evaluation and action execution. Second, this review will consider work by Trommershauser, Maloney, & Landy (2003) that investigated how people evaluate visuomotor options in the presence of uncertainty. Thirdly this review will consider work by Byrne & Crawford (2010) that looked at how different types of information are combined in order to plan a motor response. Lastly this review will end by introducing a visuomotor paradigm and a set of questions that bring together the issues of how we select (1) which action is best in the presence of uncertainty, (2) when to execute that action, and (3) how different characteristics of options are combined/used in order to make a decision.

Battaglia & Schrater (2007) used a timed reaching task to investigate whether or not subjects could optimally balance viewing and motor time. In their task, subjects start with their finger on a button in the upper right portion of a frontoparallel workspace with a visual stimulus projected onto it. On the left of the display, dots were generated one at a time from a 2-dimensional Gaussian centered on an invisible target. Once a dot was generated, it remained visible for the remainder of the trial, thus providing information about the target locations. Subjects had 1200 ms to point at where they believed the target was, based on the dots they saw. They could wait longer to improve their estimate of where to aim, but then they would need to rush the pointing which would increase their motor variability and decrease accuracy. Pointing too early might have resulted in improved motor performance but a poorer estimate of where the centroid of the 2-dimensional generative Gaussian was. This is because their estimate would be based on a set of dots with a smaller sample size than if they had waited longer.

They found that subjects adjusted their decision of when to reach optimally so as to reduce reaching errors. Subjects did this whether they were given feedback or not.

Battaglia & Schrater (2007) interpreted this to mean that subjects were relying on internal estimates of performance rather than learned associations between timing choices and trial outcomes. Ultimately their work showed that subjects' internal estimates of motor performance (i.e. reaching ability) seemed to be represented as functions of time. The next article that will be reviewed has also found evidence suggesting that subjects rely on internal performance estimates when selecting among options for a motor response.

Trommershauser, Maloney, & Landy (2003) investigated subjects' ability to use internal estimates of their motor variability when planning a reach towards a display containing a penalty and reward region. On each trial subjects had to point toward a green reward region without hitting a red penalty region, in under 700ms. The amount of overlap between the two regions, as well as the difference in the reward and penalty values was manipulated. They found that subjects' reach endpoints took into consideration their own motor variability in order to point at the optimum spot so as to maximize expected gain. In addition subjects reach endpoints were sensitive to the reward and penalty values. In other words, larger penalties resulted in larger shifts of reach endpoints away from the penalty region. This work shows that subjects use internal estimates of their own motor variability when planning motor responses. Furthermore, information derived from the motor system is effectively integrated with information from the world (e.g. reward and penalty values) when performing visuomotor tasks. The next article examines how different cues are combined and the use of heuristics in planning a reach toward a remembered target location.

Byrne & Crawford (2010) had subjects point toward a remembered target location in the presence of landmarks in order to examine how egocentric (relative to self) and allocentric (relative to external landmarks) cues are combined when planning where to reach. They were also interested in the use of a heuristic that excessively down-weighted allocentric cues that were deemed unstable (moving a lot during target presentation). They also introduced shifts of landmark locations during the trial in order to produce conflict between egocentric and allocentric information. Firstly, they found that subjects' reaches were affected by both egocentric and allocentric cues. Secondly they found that subjects' reaches combined egocentric and allocentric information optimally when landmarks were perceived as stable (moving very little during target presentation). Lastly they found that when landmarks moved a lot during target presentation (unstable) there was excessive discounting of allocentric information. This work suggests that subjects can combine different sources of information successfully but that certain conditions exist that elicit the use of heuristics in visuomotor tasks.

The current set of experiments aims to answer the following questions: (1) do subjects use internal performance estimates when selecting among a set of options in a visuomotor task?, (2) Do they split time efficiently between choosing the best option and executing a motor response?, (3) do heuristics exist in deciding which option is best? and (4) in what ways are eye movements used in the selection process as well as during execution of the motor response?

The basic paradigm used throughout both experiments presented here is a virtual shooting game in which subjects have a limited amount of time to select a target between two moving options, and then shoot at it with a “gun” controlled by a mouse. Targets vary in size and pattern of motion. If subjects rely on internal performance estimates when selecting a target to shoot at, their choices should be consistent with a model that maximizes the probability of a hit, as estimated from their own data. If subjects apportion time between deciding and shooting in a way that maximizes task performance (i.e. probability of hitting the target), their decisions should reflect a sensitivity to the impact of time on the ability to discriminate which option is best as well as on shooting performance. If heuristics exist in visuomotor decision making, subjects may show a preference to excessively rely on size or motion when making their decisions. Eye movements may be used to select or just to assist in aiming, depending on the quality of peripheral analysis as well as the difficulty of discrimination. The current study employs eye tracking and psychophysics in order to address these issues and introduce novel results in the field of visuomotor decision making.

2. Experiment 1: Predictable vs. unpredictable targets

The first experiment utilized stimuli that varied in terms of the predictability of their motion trajectories. This is an interesting variable because it allows for evaluating the utility of information vs. physical attributes such as size. Is it easier to hit a small predictable target or a large unpredictable target? Are subjects sensitive to these differences?

Methods

Eye movement recording

Eye movements were recorded using the Eyelink 1000 (SR Research, Osgoode, Canada), tower mounted version, sampling at 1000 Hz. Stimuli were presented on a Viewsonic G90fb CRT monitor, 1280 x 1024 resolution, 60 Hz refresh rate, located at a viewing distance of 119 cm. The display area subtended 15.5° horizontally by 12.4° vertically. A chin rest was used to stabilize the head. Eye movements were recorded from the right eye.

Stimuli

Stimuli consisted of one or two moving white discs ('targets') on a black background. A white oriented line served as a 'gun'. One end of the line was in contact with and moved along an arc at the bottom of the screen. The 'gun' rotated along the arc, with the position controlled by a computer mouse (Fig. 1). Targets varied in radius (7, 15, 22, 29, and 36 minarc). Target positions were updated at 6 Hz, where the amplitude of displacement at each position update was constant within a trial and randomly selected from the values 7, 22, 36, 51, and 65 minarc. The pattern of target motion was randomly selected to be either noisy (turning angle sampled uniformly at each position update) or predictable (circular trajectory with constant location and motion radius throughout all trials). The initial position of the target was either the upper left, or upper right quadrant 8.25° from the gun starting location. Target motion was restricted so that the target (1) remained on the screen (2) did not cross the vertical mid line of the display, and (3) did not move below the highest point of the arc at the bottom of the screen. These restrictions were implemented by resampling turning angle uniformly until the new target position satisfied these constraints. These restrictions allowed for easy determination of which target subjects intended to hit.

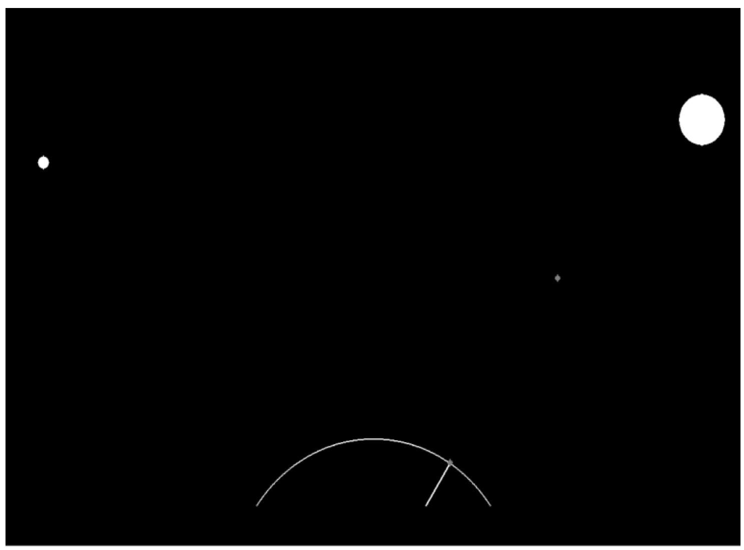

Figure 1. Stimulus configuration for experiment 1 (two-target version). In this example a small target can be seen in the upper left and a larger target can be seen in the upper right. The gun has been fired at the bottom of the screen and the small grey bullet can be seen on its way to missing the target on the right.

The ‘bullet’ was a small grey disc that began moving from the upper end of the gun when the subject left clicked the mouse when the left mouse button was pressed. The bullet traveled at a constant velocity of 14.5°/s.

Procedure

Each subject was tested in multiple 50-trial sessions taking place over the course of a 10 week period. Subjects first ran in the one-target version. Initial target position was either the left or right side of the screen (selected randomly). After ~2000 one-target trials the two-target version of the experiment was run. The instructions were to try to hit a target on every trial. Feedback was given in the form of both the view of the bullet as well as a post-trial message indicating "HIT","MISS", or "TOO SLOW". In the two-target conditions additional feedback at the end of each session indicated the percentage of trials in which a hit was achieved.

The one-target version of the experiment was run at two different durations; 1 and 1.5s. This duration was the time available for aiming and shooting and did not include bullet travel time. Trials were blocked by duration into 8 50-trial sessions with a short (1 minute) break every 4 sessions and a longer (5 minute) break in between blocks with different trial durations. After all data were collected for the one-target condition, the two-target version was tested. Trial duration was 3s. Blocks of 8 50-trial sessions were run with the same break intervals as the one-target condition.

The order of events in a trial was the same for the one and two target conditions. The calibration routine built into the Eyelink software was run before the start of each 50-trial session. After the calibration, subjects fixated a white cross on a black background located at the future position of the gun starting point (where the upper end of vertically oriented gun intersects the arc). Subjects began the trial when ready by a right-click of the mouse. Then, either 1 or 2 targets appeared (depending on the condition) and began moving immediately. The target characteristics (size, velocity, and motion pattern) were selected randomly on each trial. Subjects aimed the gun by moving the mouse to the left or right and fired by left-clicking the mouse. After the gun was fired, or the trial deadline was reached, there was a delay of 1s where the bullet traveled to its endpoint. Feedback ("HIT","MISS", or "TOO SLOW") was displayed for 333ms. Then, a fixation cross appeared to signal it was time for the next trial. The gun was reset to its vertical position every trial.

Subjects

Four subjects (paid Rutgers University students) were tested. All had normal vision, and were naïve to the experimental design and hypothesis. Results from the 4 individual subjects will be identified by an arbitrary two letter code (SB, SS, JA, MB). All subjects were right handed and always use the mouse with their right hand (as they did in this experiment as well). Procedures were approved by the Rutgers University IRB.

Analysis

The beginning and ending positions of saccades were detected offline by means of a computer algorithm employing a velocity criterion to find saccade onset and offset. The value of the criterion was determined empirically for individual observers by examining a large sample of analog recordings of eye positions. Eye movement data will be analyzed in a later paper.

Experiment 1: Results

Single target

The ability to hit the target was determined by both target size and velocity. Figure 2 shows the probability of a hit for all 4 subjects tested, with the predictable motions (left column) and noisy motions (right column). Probability of a hit is shown as a function of target velocity with separate functions drawn for each target size. The probability of a hit declined as target velocity increased and target size decreased for both noisy and predictable target motions. A logistic regression (on noisy target motions) revealed that all subjects showed significant effects of both target size and velocity on p(hit) (Table 1). Specifically, increases in target size led to significant increases in the log odds of a hit, whereas increases in target velocity led to significant decreases in the log odds of a hit.

Performance with the predictable motions proved to have an unexpected characteristic, namely, subjects appeared to adopt a strategy of waiting for the target to cross the estimated path of the bullet (see below for more details). For this reason, the statistical analyses below focus mainly on performance with the noisy motions and Experiment 2 will use motions that did not appear to be amenable to this special strategy.

Table 1.
Logistic regression results for noisy target motions.

Subject	**Size**	**Velocity**
JA	$\beta = 0.05, p < .0001$	$\beta = -0.02, p < .0001$
MB	$\beta = 0.05, p < .0001$	$\beta = -0.01, p < .0001$
SB	$\beta = 0.05, p < .0001$	$\beta = -0.01, p < .0001$
SS	$\beta = 0.05, p < .0001$	$\beta = -0.01, p < .0001$

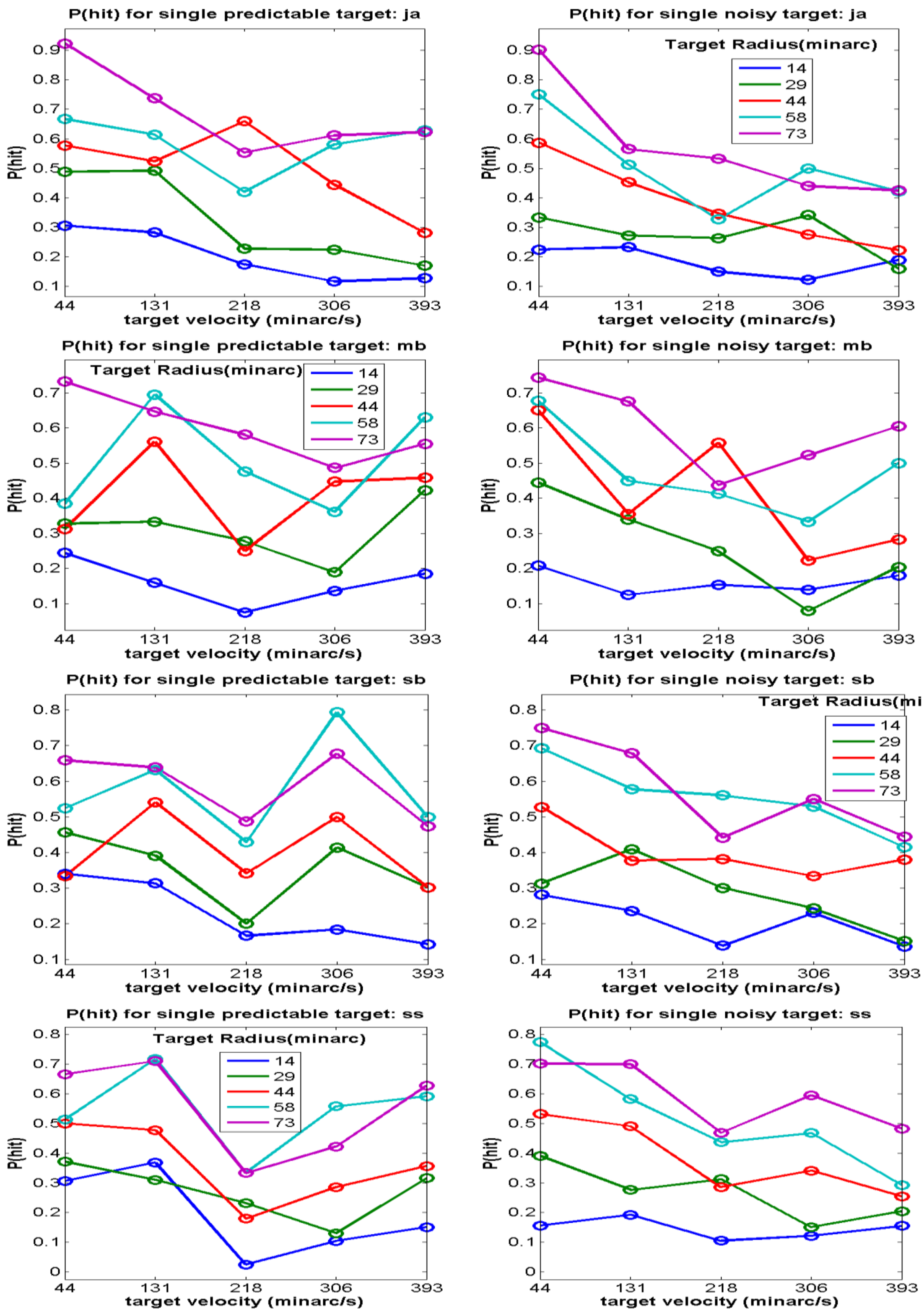

Figure 2. Probability of hit plotted as a function of velocity for noisy (left) and predictable(right) motions. Different lines represent different target sizes. Different rows represent different subjects.

Effects of the conditions on reaction time were less consistent than effects on P(hit) (Figure 3 and Table 2). Reaction time was computed as the time between target presentation and when the subject fired the 'gun'. Two-Way ANOVAs on noisy target motions revealed that larger targets elicited significantly shorter RTs for JA and SS (p's < 0.004), but not for MB and SB. Faster targets elicited significantly shorter RTs for SB (p=0.01), but no one else. There were no significant interactions between size and velocity.

Table 2.

Two-Way Analysis of Variance results for Reaction time for noisy target motions.

Subject	Size	Velocity
JA	**$F(4,1051) = 3.91, p = 0.0037$***	$F(4,1051) = 2.35, p = 0.0524$
MB	$F(4,1085) = 1.42, p = 0.2265$	$F(4,1085) = 1.88, p = 0.1125$
SB	$F(4,981) = 0.59, p = 0.6678$	**$F(4,981) = 3.14, p = 0.0139$***
SS	**$F(4,1103) = 5.75, p = 0.0001$***	$F(4,1103) = 1.09, p = 0.3588$

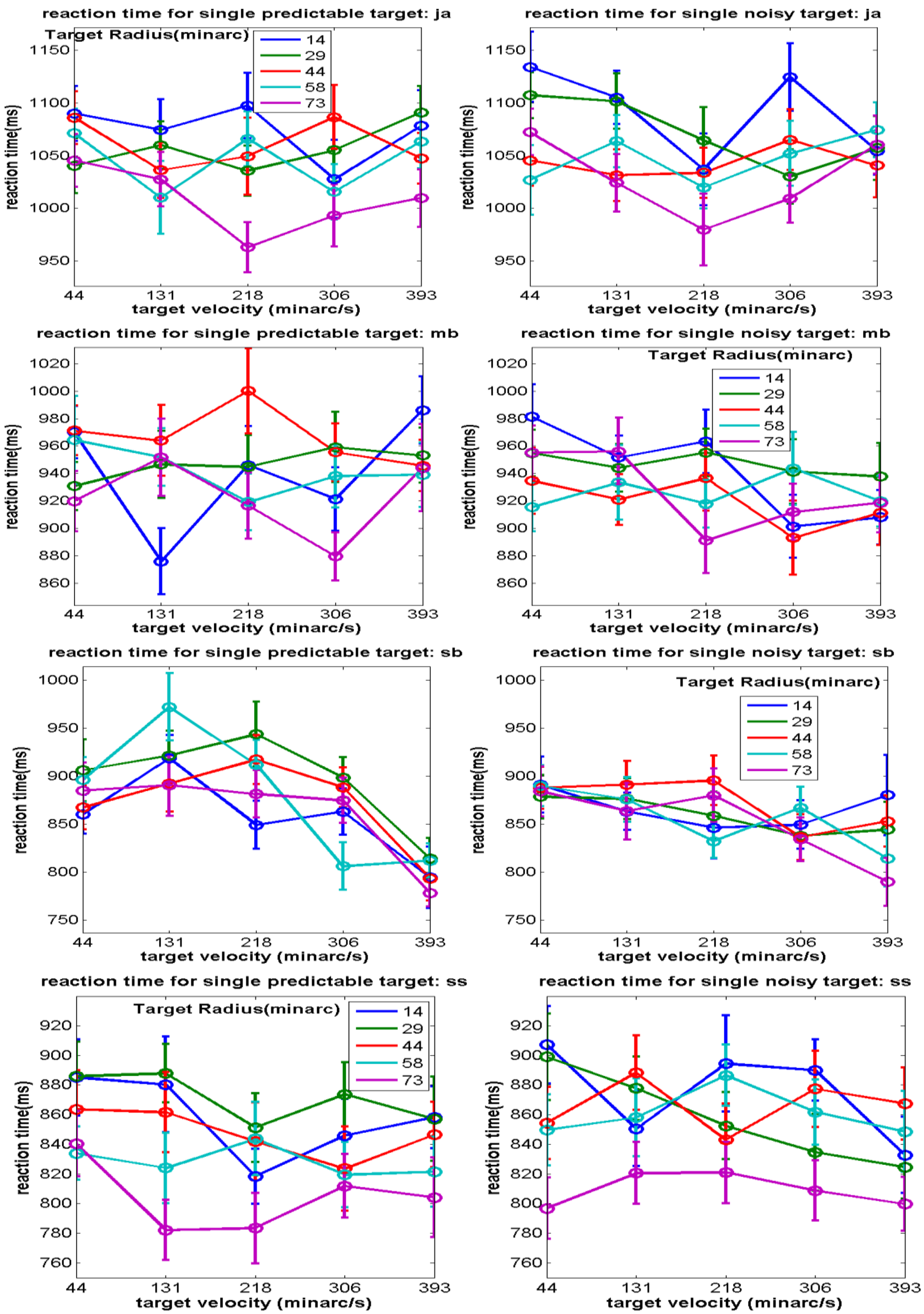

Figure 3. Reaction time plotted as a function of velocity for noisy (left) and predictable(right) motions. Different lines represent different target sizes. Different rows represent different subjects.

Shooting accuracy was significantly worse for faster targets. Shooting accuracy was measured as the minimum Euclidean distance between bullet- and target-center for trials in which subjects fired the gun before the deadline. All subjects showed strong effects of velocity on accuracy but no effects of size (Figure 4 and Table 3). This suggests that subjects did not adjust their aiming strategy for larger or smaller targets, but instead always intended to hit the center of the target. Error increased as velocity increased for noisy target motions for all subjects.

Table 3.
Two-Way Analysis of Variance results for Shooting Accuracy for noisy target motions.

Subject	Size	Velocity
JA	$F(4,1051) = 0.25, p = 0.91$	**$F(4,1051) = 23.07, p < .00001$***
MB	$F(16,1085) = 0.69, p = 0.60$	**$F(16,1085) = 24.75, p < .00001$***
SB	$F(16,981) = 1.87, p = 0.11$	**$F(16,981) = 19.45, p < .00001$***
SS	$F(16,1103) = 1.06, p = 0.38$	**$F(16,1103) = 22.46, p = < .00001$***

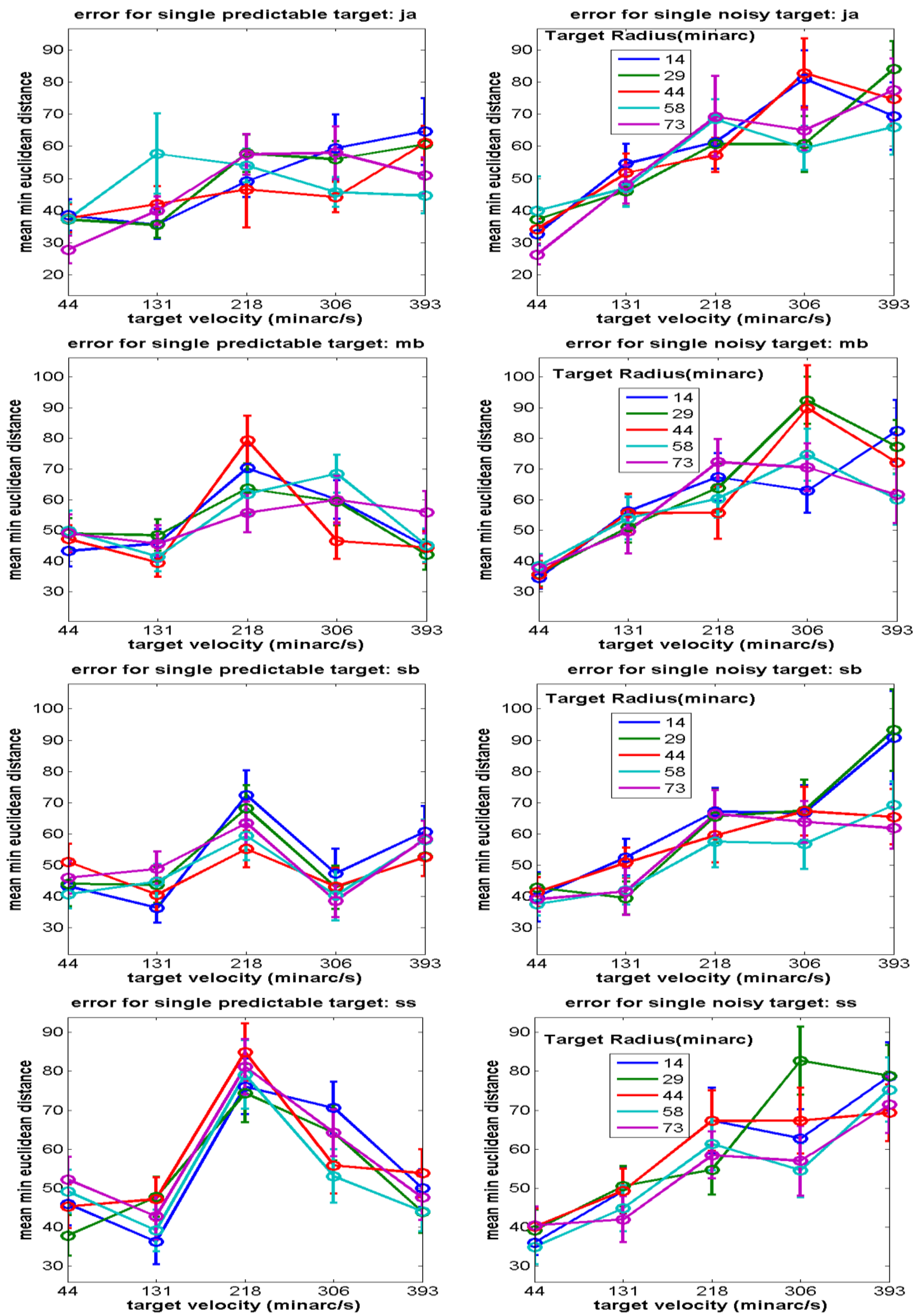

Figure 4. Shooting error plotted as a function of velocity for noisy (left) and predictable(right) motions. Different lines represent different target sizes. Different rows represent different subjects.

For predictable target motions 3 of 4 subjects showed an increase in error at a velocity of 50 pixels/update and then a decrease for higher velocities (Figure 4 right panels). As noted above, it is possible that this pattern was a result of attempts to use a particular shooting strategy. Figure 5 shows that subjects tended to position the gun at a tangent to the inferred counter-clockwise circular motion path and then fire at the target as it turned the corner, thus reducing motion perpendicular to the gun. This strategy may have only been employed for targets at medium velocities because slower targets would run out the trial duration and faster targets may have been too difficult to hit in this manner. This strategy was not anticipated and accounts for why Experiment 2 did not use such predictable motions and why the analyses below of the two-target condition will be restricted to the noisy motion.

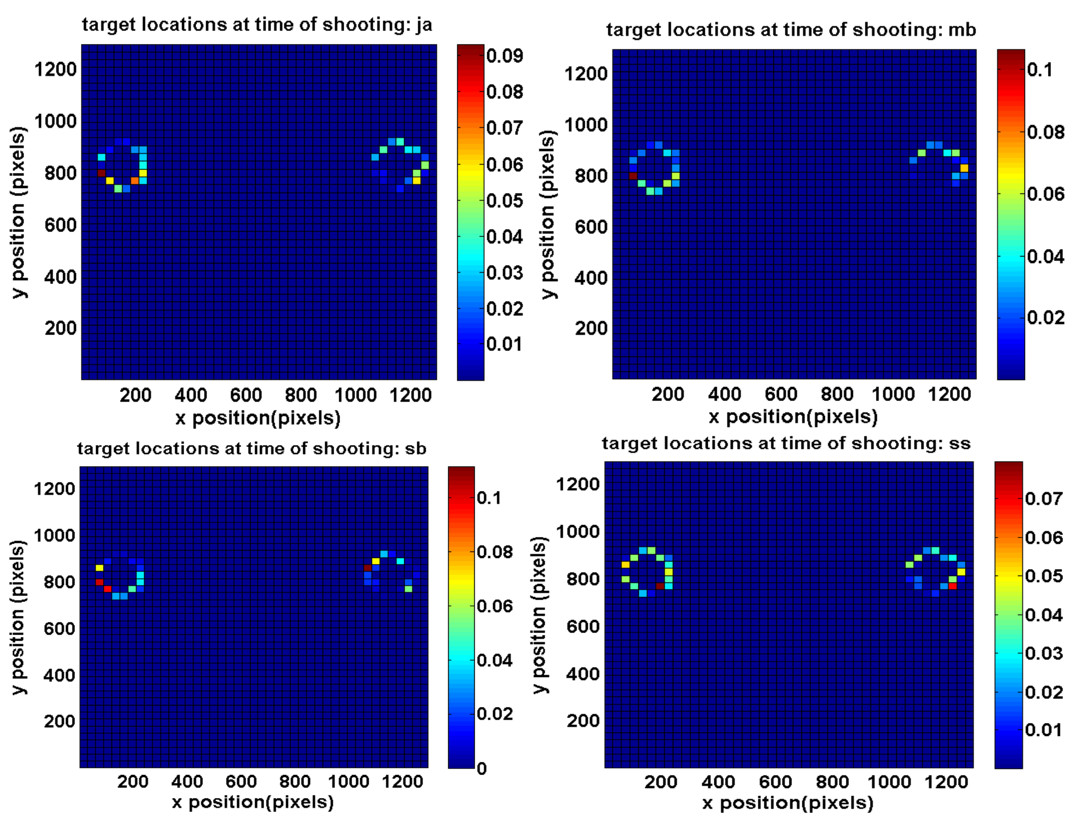

Figure 5.Target locations at the time each subject fired the gun. Data shown are for predictable motion targets only.

Two targets

For two-target trials, the best strategy to maximize the probability of a hit would be to aim at the easier target. In the two-target trials, subjects overall shot at the easier target (the target with a higher hit probability in the single target trials) on 73% of the trials (averaged across 4 subjects). Figure 6, left, shows the probability of aiming at the easier target as a function of the difference in P(hit), where P(hit) is taken from the single target performance. The probability of aiming to the easier target increased as a function of the difference in p(hit) for the two targets. Figure 6 shows that subjects aimed at the easier target on 75% of the trials when the difference in P(hit) for each target reached .14 to .25. These small values show that the choice did take into account the evaluation of performance with the single targets. Figure 6, right, shows reaction time again as a function of the difference in P(hit) values for each target. Subjects made decisions more quickly when there was a larger discrepancy between the hit probabilities of the two targets.

Overall the two target results show that subjects were able to select the target with a higher probability of a hit, although this discrimination took longer when differences were small. Further analyses showed that in about 75% of trials when subjects chose to shoot at the target with a lower hit probability, they did so because their chosen target was larger. This indicates a preference to weigh the dimension of size more than velocity.

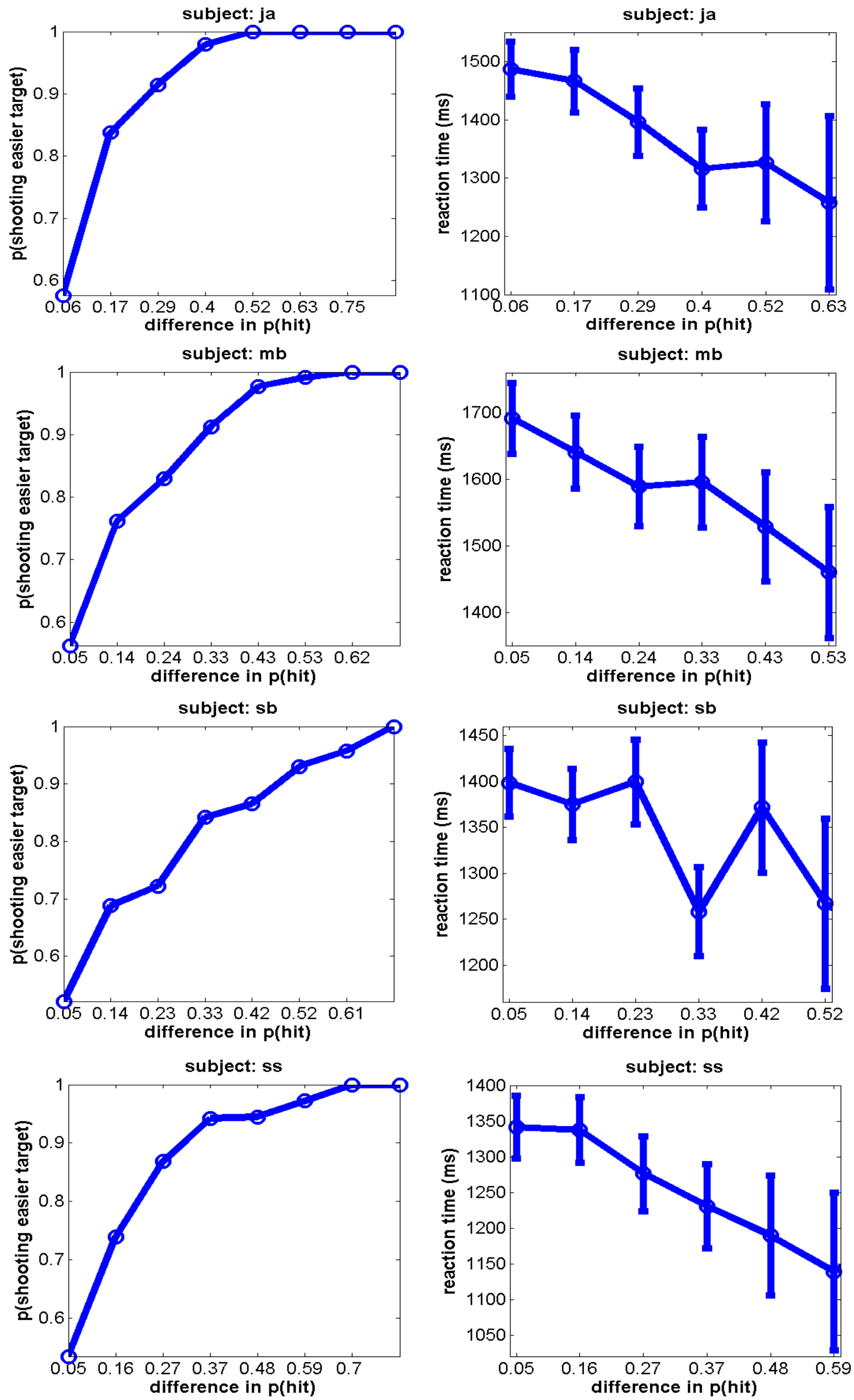

Figure 6. Probability of picking easier target (left) and Reaction time (right) plotted as a function of difference in hit probability between choices.

The logistic regressions that were run on the single target data revealed that target size had a much larger impact on subjects' ability to hit the target compared to velocity (see Table 1). Figure 7, left, shows that target size also had a much larger impact on subjects' choice of which target to aim to (right panel). These results indicate that, although both variables had a significant impact on subject's decisions, size was much more influential.

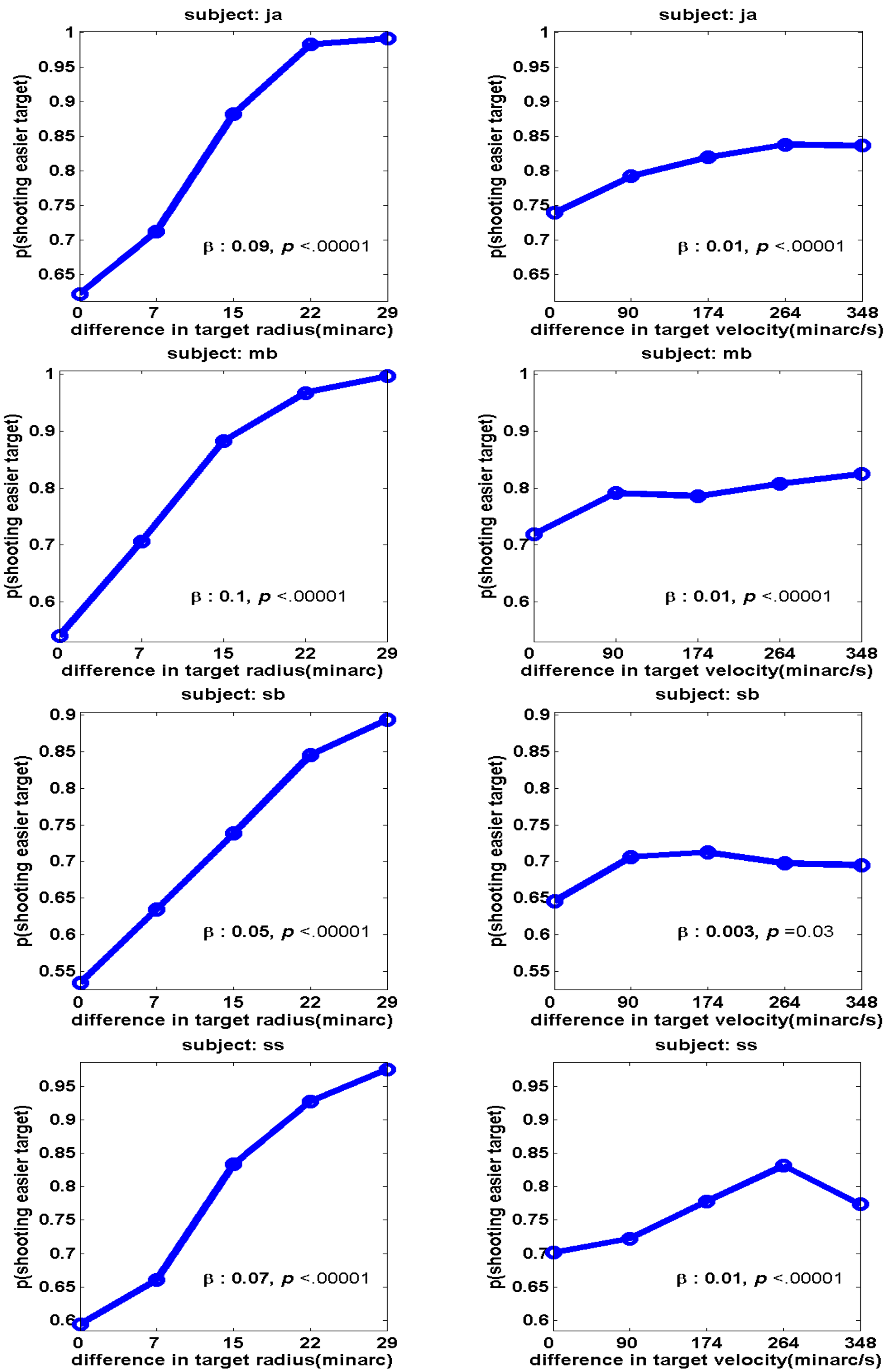

Figure 7. Probability of picking easier target plotted as a function of difference in target size (left) and velocity (right). Slopes and p-values from a Logistic regression are shown in each panel.

Discussion

Overall, subjects' choice of target in the two-target condition reflected a rational sensitivity to hit probabilities for each target. This indicates that subjects may have been using internal estimates of their own shooting performance to make their decision. However, since they had extensive experience with the single-target trials prior to the two-target sessions, this may have been due to learned associations between feedback and target type. For this reason, Experiment 2 interleaved single- and two-target blocks from the beginning.

Although subjects often chose the target that had a higher probability of a hit, there was a tendency to shoot at larger targets even though they sometimes had a lower probability of a hit. This preference may be due to the time limit imposed in each trial. Although the sizes and the velocities were easily distinguishable, subjects could make decisions more quickly by focusing on size which could be ascertained in a single frame whereas velocity requires multiple frames to achieve an accurate estimate.

3. Experiment 2: Influences of urgency

In order to examine the role of time in more detail, as well as the influences of urgency on decision making, multiple trial durations were tested in Experiment 2. I will present results with 1 target, then with 2 targets, each at 3 different trial durations. I will then address the question of whether the choice of target in the two target condition was consistent with a strategy of using time in the best way to maximize task performance.

Methods

Eye movement recording

Eye movements were recorded with the same procedure as in Experiment 1 and will be analyzed in a later paper.

Stimuli

Stimuli consisted of one or two moving white discs ('targets') on a black background. A white oriented line served as a 'gun'. One end of the line was in contact with and moved along the circumference of a white circle that subtended 2.4° and was centered at screen-center. The 'gun' rotated along the arc, with the position controlled by a computer mouse. Targets varied in diameter (14, 72, and 130 minarc). Target positions were updated at 6 Hz, where the amplitude of displacement at each position update was randomly selected from a Gaussian mixture with one component centered over small jumps (7 minarc), and another component centered over large jumps (2.4°). Targets varied in the probability of a big jump (0.1, 0.5, or 0.9). Probabilities and sizes were constant within a trial and randomly selected from one trial to the next. The initial position of the target was either middle left, or middle right, 6° from the gun starting location. Target motion was restricted so that the target (1) remained on the screen (2) did not cross the vertical mid line of the display, and (3) did not move below the bottom 25% of the screen. These restrictions were implemented by resampling turning angle uniformly until the new target position satisfied these constraints.

The ‘bullet’ was a small grey disc that began moving from the upper end of the gun when the subject left clicked the mouse when the left mouse button was pressed. The bullet traveled at a constant velocity of 14.5°/s.

Procedure

Each subject was tested in multiple 25-trial sessions taking place over the course of a 10 week period. Subjects first ran both single- and two-target sessions interleaved from the beginning. In the one-target version, initial target position was either the left or right side of the screen (selected randomly). The instructions were to try to hit a target on every trial. Feedback was given in the form of both the view of the bullet as well as a post-trial message indicating “HIT”,”MISS”, or “TOO SLOW”. In the two-target conditions additional feedback at the end of each session indicated the percentage of trials in which a hit was achieved.

The one-target version of the experiment was run at three different durations; 750ms,1s, and 3s. The two-target version of the experiment was run at the same durations as the single-target version. This duration was the time available for aiming and shooting and did not include bullet travel time. Trial duration was blocked into 8 25-trial sessions with a short (1 minute) break every 4 sessions and a longer (5 minute) break in between blocks with different trial durations.

The order of events in a trial was the same for the one and two target conditions. The calibration routine built into the Eyelink software was run before the start of each 25-trial session. After the calibration, subjects fixated a white cross on a black background located at the future position of the gun starting point (screen center). Subjects began the trial when ready by a right-click of the mouse. Then a small white square appeared at screen center and a small white disc appeared at the current mouse position. The disc could be controlled with the mouse and had to be brought into the white square and then clicked in order to proceed. This served the purpose of reorienting the mouse to the starting position of the gun. Then subjects had to fixate a white cross at screen center for 500ms. Once the fixation requirement had been met either 1 or 2 targets appeared (depending on the condition) and began moving immediately. The target characteristics (size and probability of a big jump) were selected randomly on each trial. Subjects aimed the gun by moving the mouse to the left or right and fired by left-clicking the mouse. After the gun was fired, or the trial deadline was reached, there was a delay of 1s where the bullet traveled to its endpoint. Feedback ("HIT","MISS", or "TOO SLOW") was displayed for 333ms. Then, a fixation cross appeared to signal it was time for the next trial.

Subjects

Three subjects (paid Rutgers University students) were tested. All had normal vision, and were naïve to the experimental design and hypothesis. Results from the 3 individual subjects will be identified by an arbitrary two letter code (BF, JW, and SB). SB is the same SB from Experiment 1. All subjects were right handed and always use the mouse with their right hand (as they did in this experiment as well). Procedures were approved by the Rutgers University IRB.

Experiment 2: Results

Single target

Figure 8 shows the probability of a hit in the single target case as a function of the complexity of the motion pattern, where complexity is expressed by the percentage of large jumps for a given target type. The different functions show performance for the 3 target sizes. Fig. 8 shows that P(hit) was determined by both size and probability of a big jump, with P(hit) decreasing with decreasing target size and with increasing % large jumps. A logistic regression on data from all 3 trial durations (750ms, 1s, and 3s) revealed that all subjects showed significant effects of size, probability of a big jump and trial duration on P(hit) (Table 4). Specifically, the logistic model indicated that increases in target size led to significant increases in the log odds of a hit, whereas more frequent large jumps led to significant decreases in the log odds of a hit. In addition, longer trial durations led to increases in the log odds of a hit for 2 of 3 subjects.

Table 4.

Logistic regression results for probability of a hit from all subjects and trial durations.

Subject	Trial duration	Size	P(big jump)
BF	$\beta = 0.00, p = .001$	$\beta = 0.02, p < .0001$	$\beta = -0.02, p < .0001$
JW	$\beta = 0.00, p = .0005$	$\beta = 0.03, p < .0001$	$\beta = -0.01, p = .0003$
SB	$\beta = 0.00, p = .08$	$\beta = 0.02, p < .0001$	$\beta = -0.01, p < .0001$

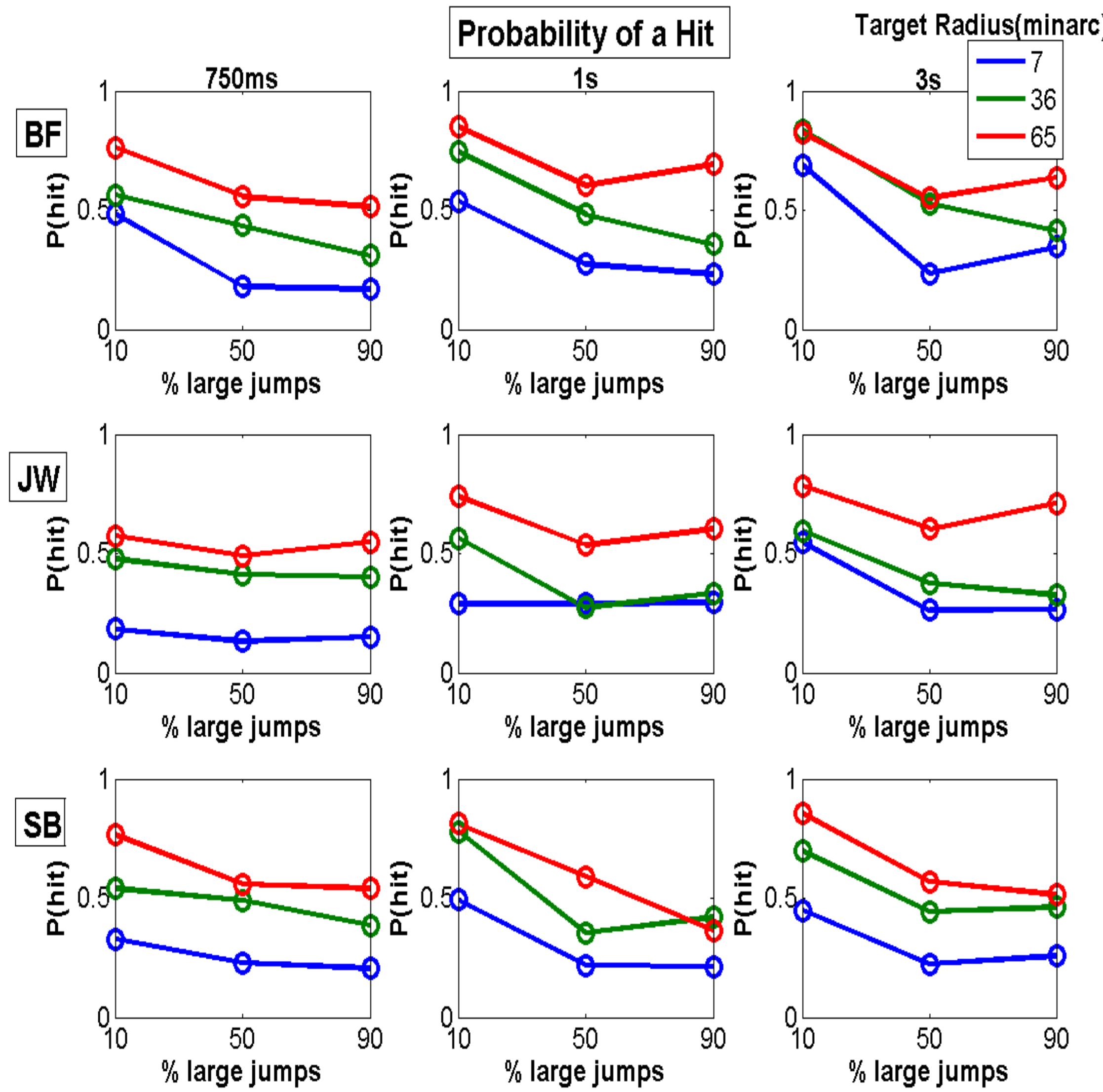

Figure 8. Probability of hit plotted as a function of % of large jumps for all subjects and trial durations. Different lines represent different target sizes. Different columns represent different trial durations and different rows represent different subjects.

Reaction time was determined by size, probability of a big jump, and trial duration (Figure 9 and Table 2). Three-Way ANOVAs on data from all 3 trial durations revealed that larger targets elicited significantly shorter RTs for all subjects. Targets with a higher probability of a big jump elicited significantly longer RTs for BF and JW but SB showed the opposite trend.

Table 5.

Three-Way Analysis of Variance results for reaction times from all subjects and trial durations.

Subject	Trial duration	Size	P(big jump)
BF	$F(2,1528) = 1303$, $p < 0.001$	$F(2,1528) = 71$, $p < .001$	$F(2,1528) = 174$, $p < .001$
JW	$F(2,1285) = 501$, $p < 0.001$	$F(2,1285) = 80$, $p < .001$	$F(2,1285) = 37$, $p < .001$
SB	$F(2,2465) = 865$, $p < 0.001$	$F(2,2465) = 248$, $p < .001$	$F(2,2465) = 16$, $p < .001$

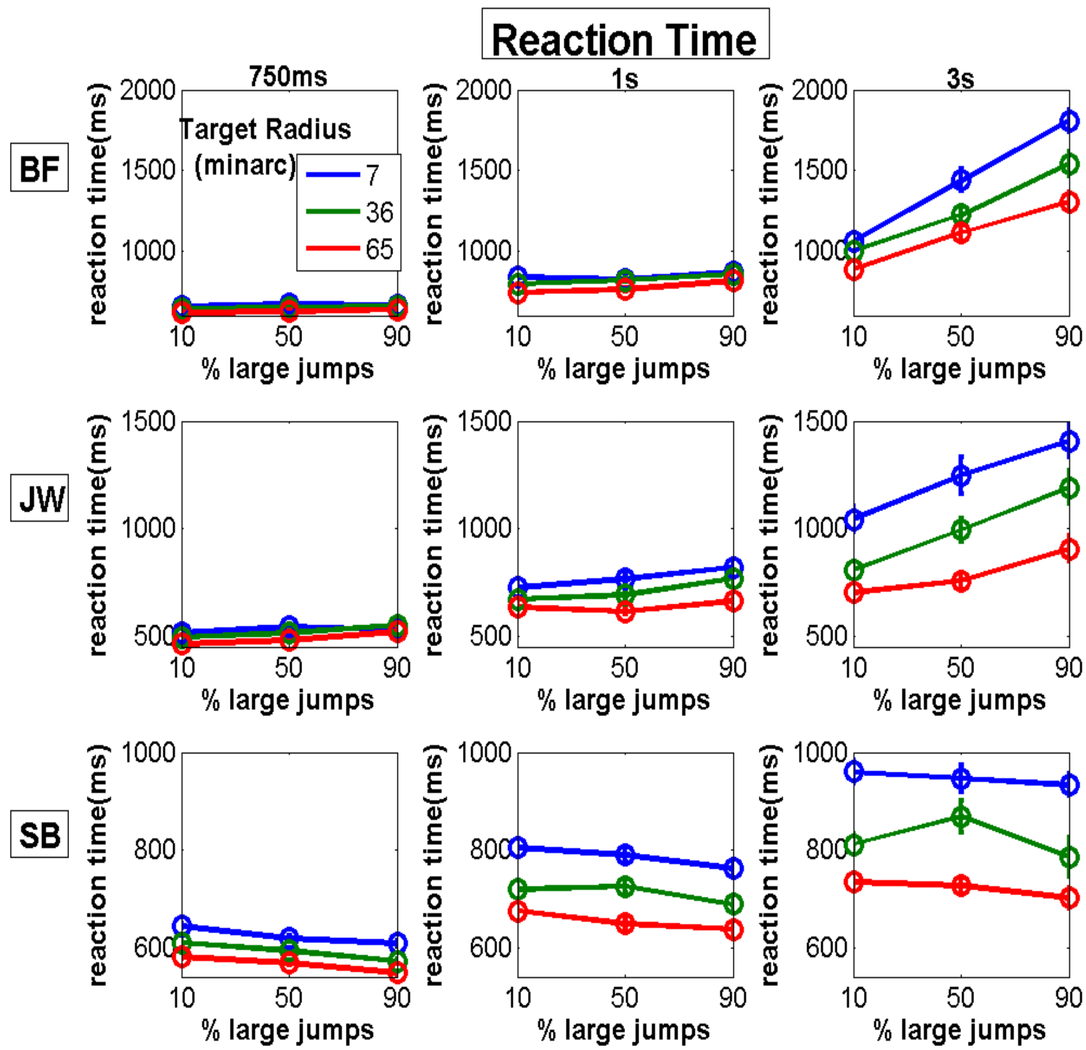

Figure 9. Reaction time plotted as a function of % of large jumps for all subjects and trial durations. Different lines represent different target sizes. Different columns represent different trial durations and different rows represent different subjects. Error bars indicate $\pm$ 1 s.e.

Figure 10 shows shooting error size, where error size refers to the minimum Euclidean distance between bullet- and target-center that was achieved on each trial. Error size increased for targets with a higher probability of a big jump. Similar to Experiment 1, no effects of target size on the size of the error were found (Figure 10 and Table 6). This suggests that subjects did not adjust their aiming strategy for larger or smaller targets, but instead always intended to hit the center of the target.

Table 6.

Three-Way Analysis of Variance results for shooting error from all subjects and trial durations.

Subject	Trial duration	Size	P(big jump)
BF	$F(2,1528) = 7.3$, $p = .0007$	$F(2,1528) = 0.5$, $p = .64$	$F(2,1528) = 63$, $p < .0001$
JW	$F(2,1285) = 9.8$, $p = .0001$	$F(2,1285) = 1.1$, $p = .32$	$F(2,1285) = 15$, $p < .0001$
SB	$F(2,2465) = 2.3$, $p = .10$	$F(2,2465) = 2.5$, $p = .08$	$F(2,2465) = 60$, $p < .0001$

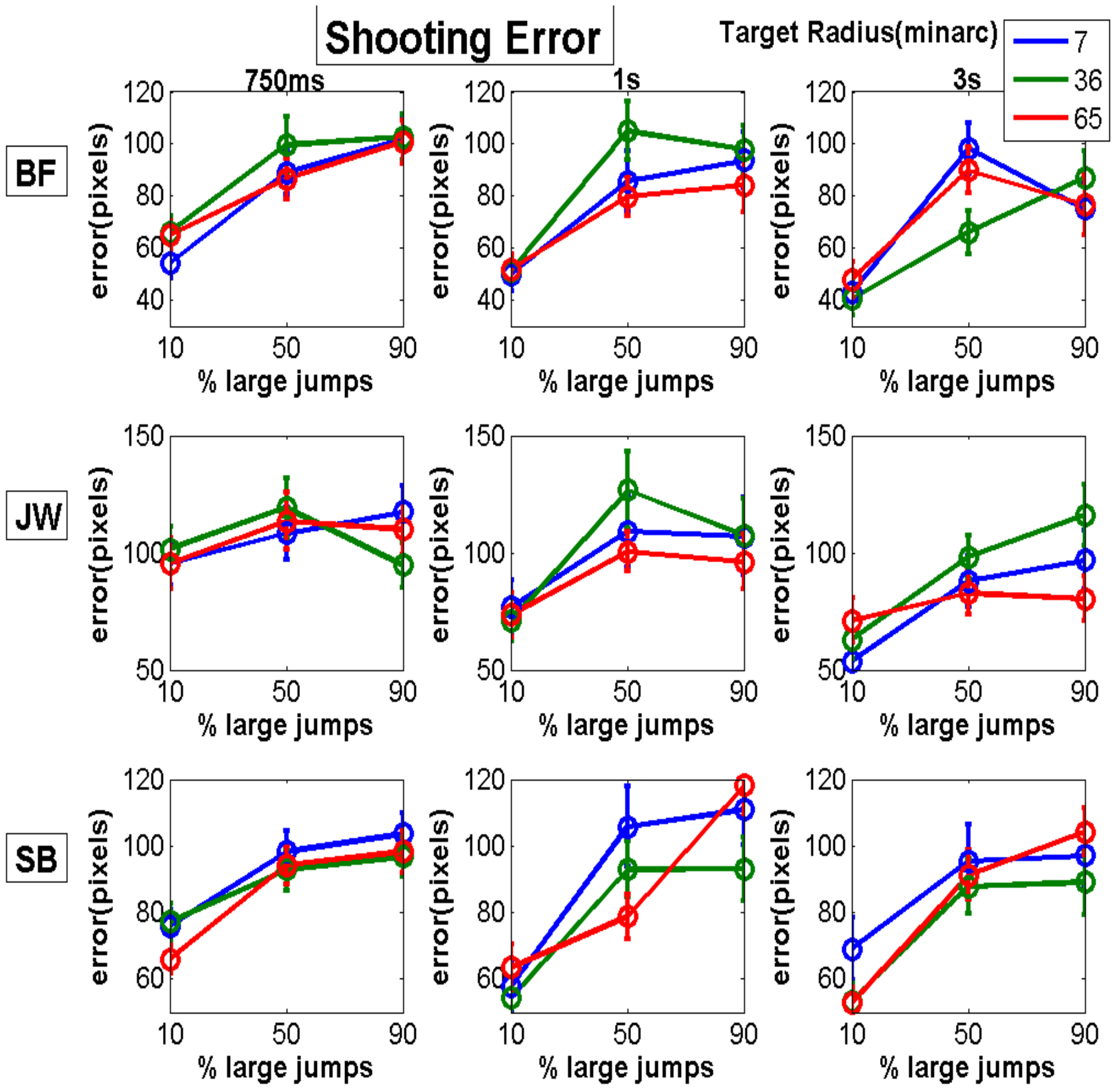

Figure 10. Shooting error plotted as a function of % of large jumps for all subjects and trial durations. Different lines represent different target sizes. Different columns represent different trial durations and different rows represent different subjects. Error bars indicate $\pm$ 1 s.e.

Summary of single target results

Single-target results revealed that size had a bigger influence on subject's ability to hit the target but that motion complexity was also significantly influential (Compare slopes in Table 4). Longer trial durations lead to significant increases in P(hit) for 2 of 3 subjects (SB did not do significantly better at longer trial durations despite having significantly longer reaction times).

Two targets

Figure 11 shows the probability of shooting at the easier of the two targets as a function of the differences in the P(hit), where P(hit) was taken from the single target trials. Results were pooled over the three trial durations. Fig. 11 shows that the probability of aiming at the easier target increased as a function of the difference in the probability of hitting each target [P(hit)] , with the probability of aiming at the easier target reaching 75% of trials for differences in P(hit) of about .2. In two-target trials, subjects overall shot at the target with a higher hit probability on 70% of the trials (average of all values in Table 7). Table 7 shows that the tendency to shoot at the target with a higher hit rate increased with trial duration for all subjects.

Reaction times are shown in Fig. 11, right panels. Overall, RT decreased as the difference in P(hit) increased.

Table 7.
% of trials in which subjects shot at target with higher hit rate in all 3 trial durations.

Subject	**750ms**	**1s**	**3s**
BF	67	74	73
JW	57	72	77
SB	70	62	75

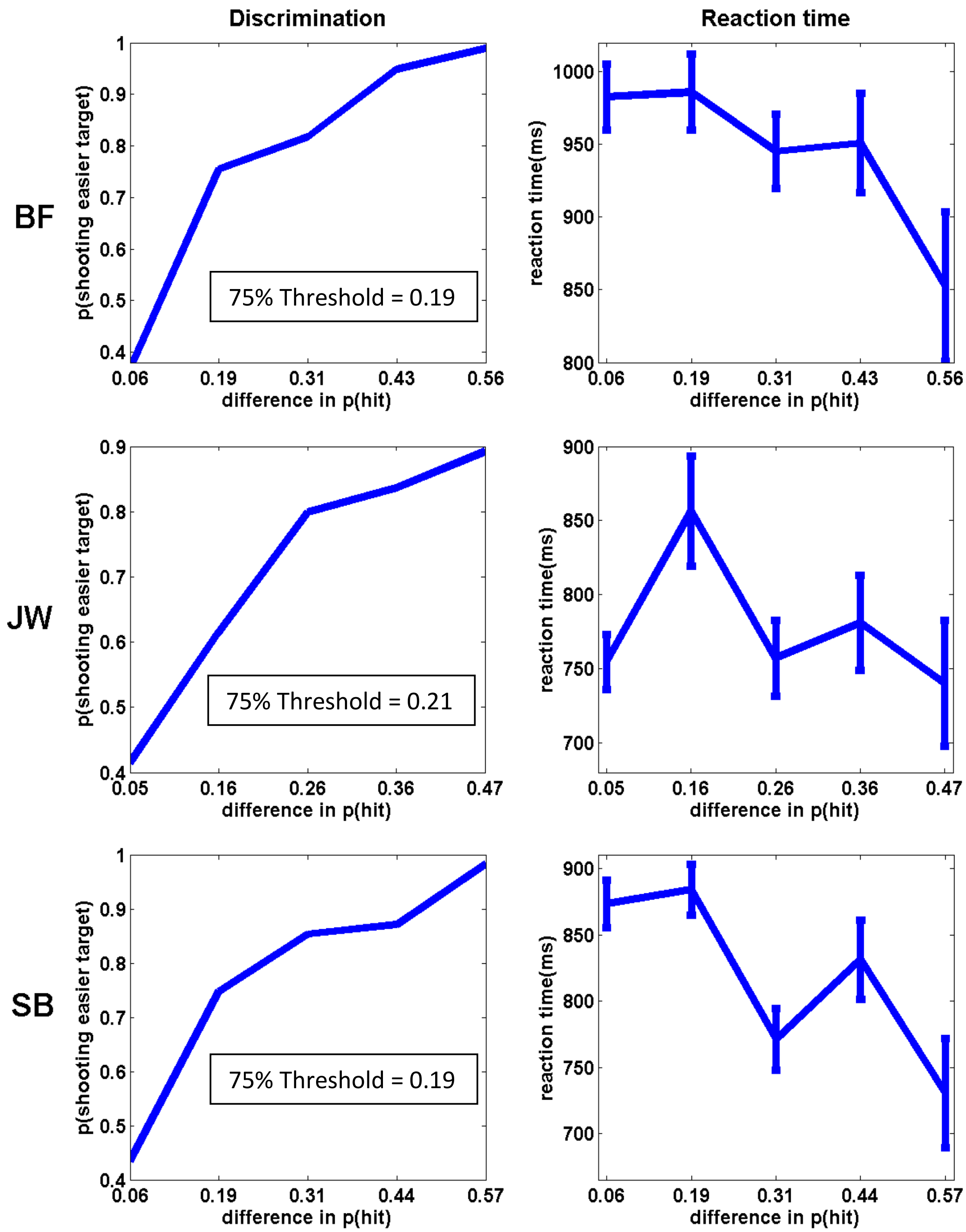

Figure 11. Probability of picking easier target (left) and Reaction time (right) plotted as a function of difference in hit probability between choices for all subjects (rows). Data shown are collapsed across all trial durations.

Bias to shoot at larger targets

Further analyses showed a bias for choosing the larger target. 87% of wrong decisions in 750ms trials could be accounted for by subjects choosing the larger, but more difficult, target. In 3s trials this percentage dropped to 73%. This replicates the preference for larger targets found in Experiment 1 and shows that it is strongest when subjects were under greater time pressure. Figure 12 shows that differences in target size (left side) had a larger influence on subjects' tendency to shoot at the target with a higher hit rate, compared to differences in the probability of a big jump (right side).

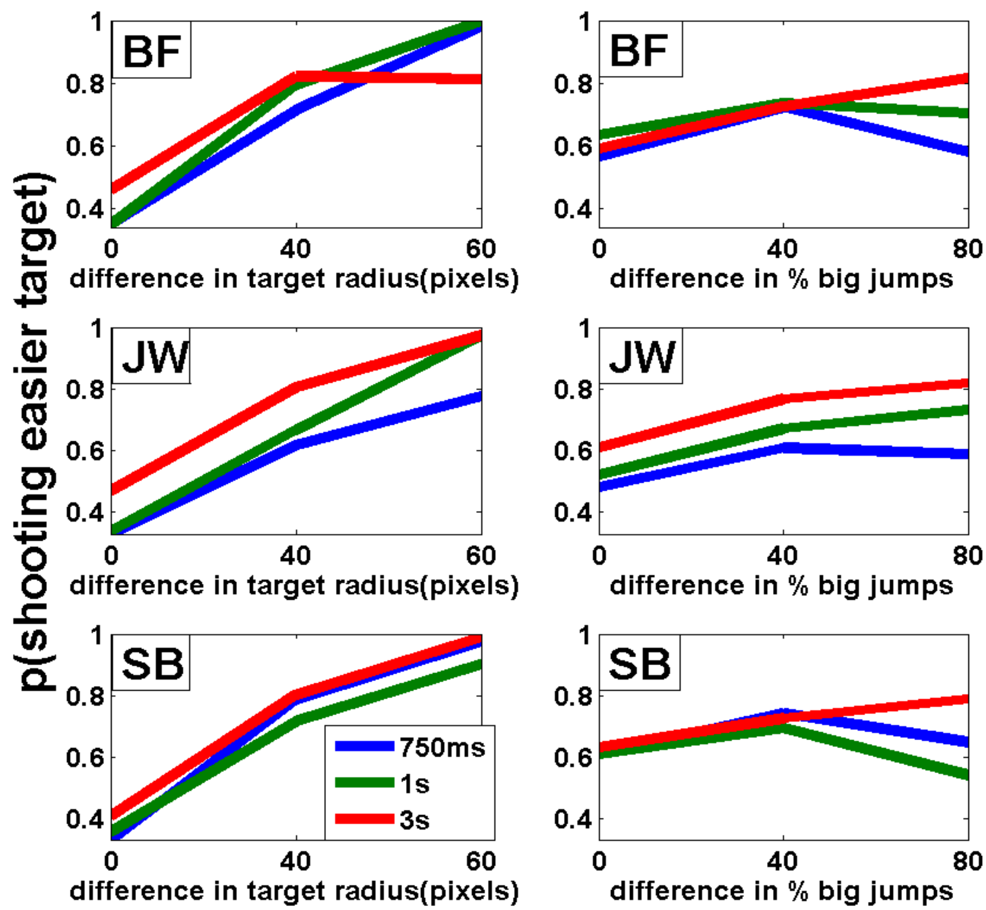

Figure 12. Probability of picking easier target plotted as a function of difference in target size (left) and difference in probability of a big jump(right). Each line represents data from sessions with different trial durations (blue=750ms, green= 1s, red=3s). Each row represents data from a different subject.

Subjects showed a tendency to shoot at larger targets even though they had a lower probability of a hit. Furthermore, this tendency was strongest at short trial durations. The following sections will examine the influence of trial duration on decision and aiming strategies.

Decision and aiming strategies

Decision and aiming strategies were analyzed further. The goal of these analyses was to determine how the conditions affected decision making and time management. The following analyses will investigate how trial duration, decision difficulty, and target difficulty influenced how subjects apportioned time among three processes: deciding, aiming, and shooting, where “deciding” refers to the choice of which target to shoot, “aiming” refers to the adjustments of gun position in the attempt to hit the chosen target accurately and “shooting” refers to the final phase where the gun is relatively stationary except for perhaps some fine adjustments and the trigger is pulled.

These phases will be distinguished by analyzing gun velocities. Gun velocities were computed as the change in gun angle in degrees/s for the first 333 ms of the trial and during the final 333ms before subjects pulled the trigger. Velocities were calculated as the slope of the best fit line for the angle of the gun in 4 consecutive frames. Then this kernel was stepped forward 1 frame and a new slope was computed. This was done iteratively throughout a given trial for all trials and subjects. These velocities can be seen in Figures 13-15 for subjects BF, JW, and SB respectively. Figures 13-15, left side, show velocities during the first 333 ms of the trials. The different lines represent trials with different levels of discriminability between target hit rates. These early velocities are useful in finding the initial latency to begin pointing the gun. Figures 13-15, left, show that subjects BF, JW, and to a lesser extent, SB, began to make rapid changes in gun angle earlier in shorter trials (top-left compared to bottom-left). This indicates that one adjustment to the time pressure in the shorter trials was to reduce the latency to initiate the response. No systematic differences were found between trials with large discrepancies in hit-rates between targets (black lines) and trials in which targets had more similar hit rates (blue lines). The shorter latencies observed in 750ms trials have no real cost since subjects were not yet committed to a response. The fact that the level of difficulty didn't affect these latencies suggests that subjects were initiating the process earlier for the shorter trials.

Velocities were also examined for the final 333 ms of the trial. This analysis can reveal when the decision was made to finally shoot. The reason is that the trigger would be pulled when the mouse (gun) stopped moving. Comparing the performance in the three rows on the right side of Figures 13-15 show that all subjects stopped making rapid adjustments in gun angle much earlier in longer trials (bottom-right) compared to shorter trials (top-right). Overall subjects average velocities fell below 200 deg/s about 200ms earlier in 3s trials compared to 750ms trials. This indicates that subjects left more time for fine tuning gun position in the longer trials and were rushing their shooting in shorter trials.

Velocities were also affected by both the size and the motion complexity of the targets that subjects chose to shoot at. Each line in the graphs in the right column of Figures 13-15 represents the characteristics of the target that the subject shot at. All subjects had a higher average peak velocity for the target with the highest hit rate. This can be seen by finding the blue knotted line in each panel on the right. This line corresponds to the largest, most stable target.

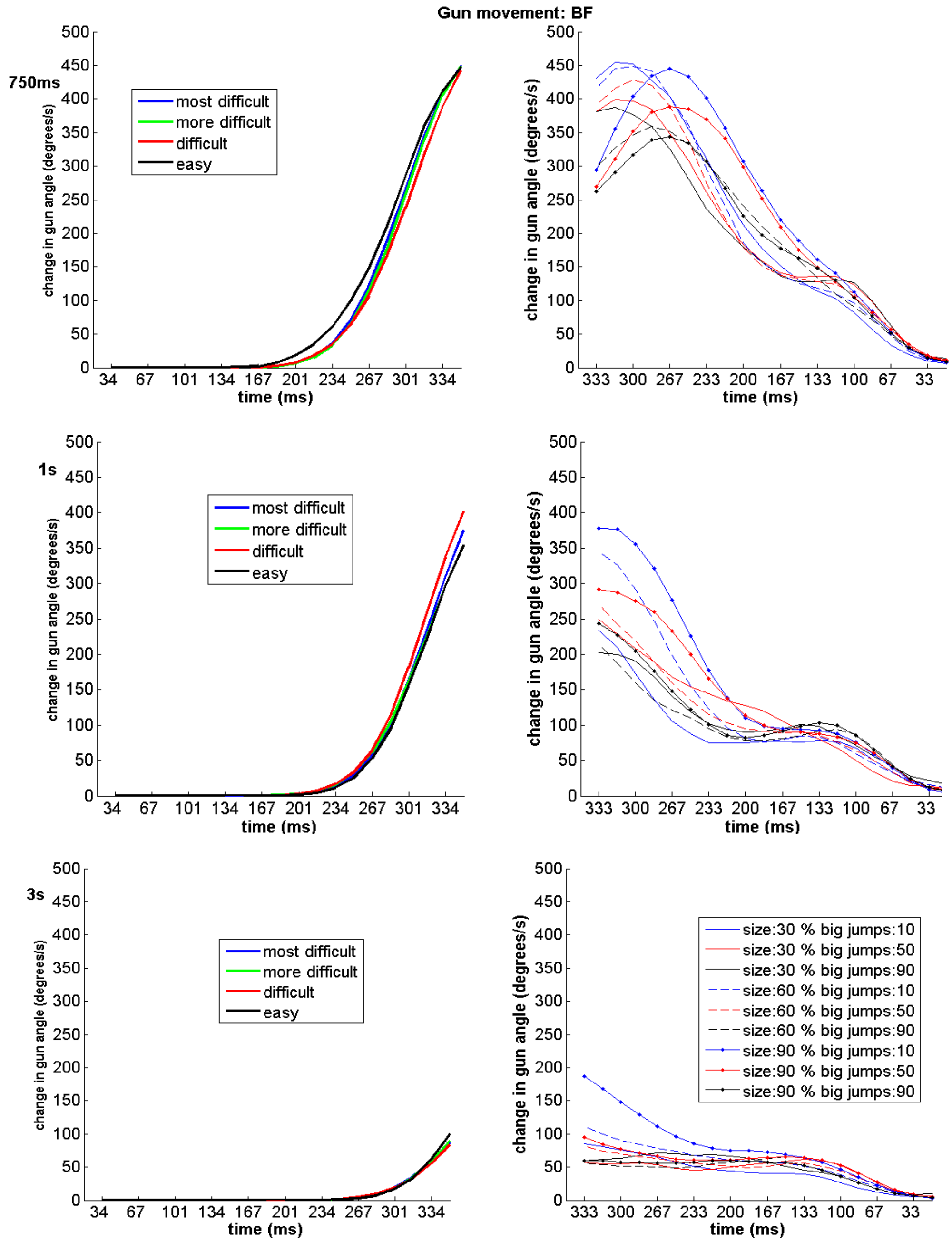

Figure 13. Gun velocities at different times in the trial for subject BF. Left side panels show gun velocities from the start of the trial until 333ms after the start of the trial. Different lines represent trials with different levels of discriminability between target hit rates. Right side panels show gun velocities looking back 333ms from the time BF fired a shot. Different lines represent different target types. Different rows display data from different trial durations. All data are from two-target trials.

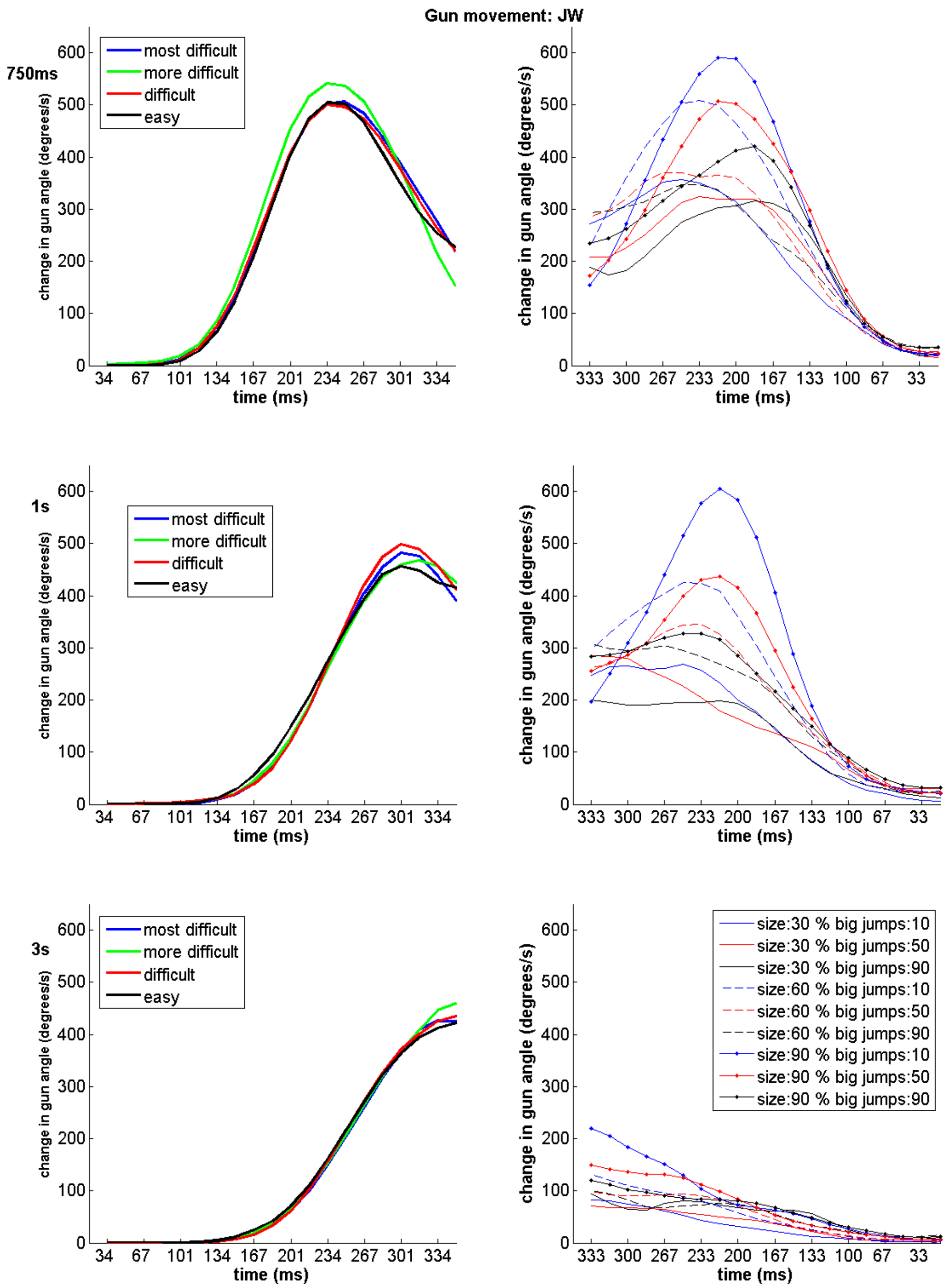

Figure 14. Gun velocities at different times in the trial for subject JW. Left side panels show gun velocities from the start of the trial until 333ms after the start of the trial. Different lines represent trials with different levels of discriminability between target hit rates. Right side panels show gun velocities looking back 333ms from the time JW fired a shot. Different lines represent different target types. Different rows display data from different trial durations. All data are from two-target trials.

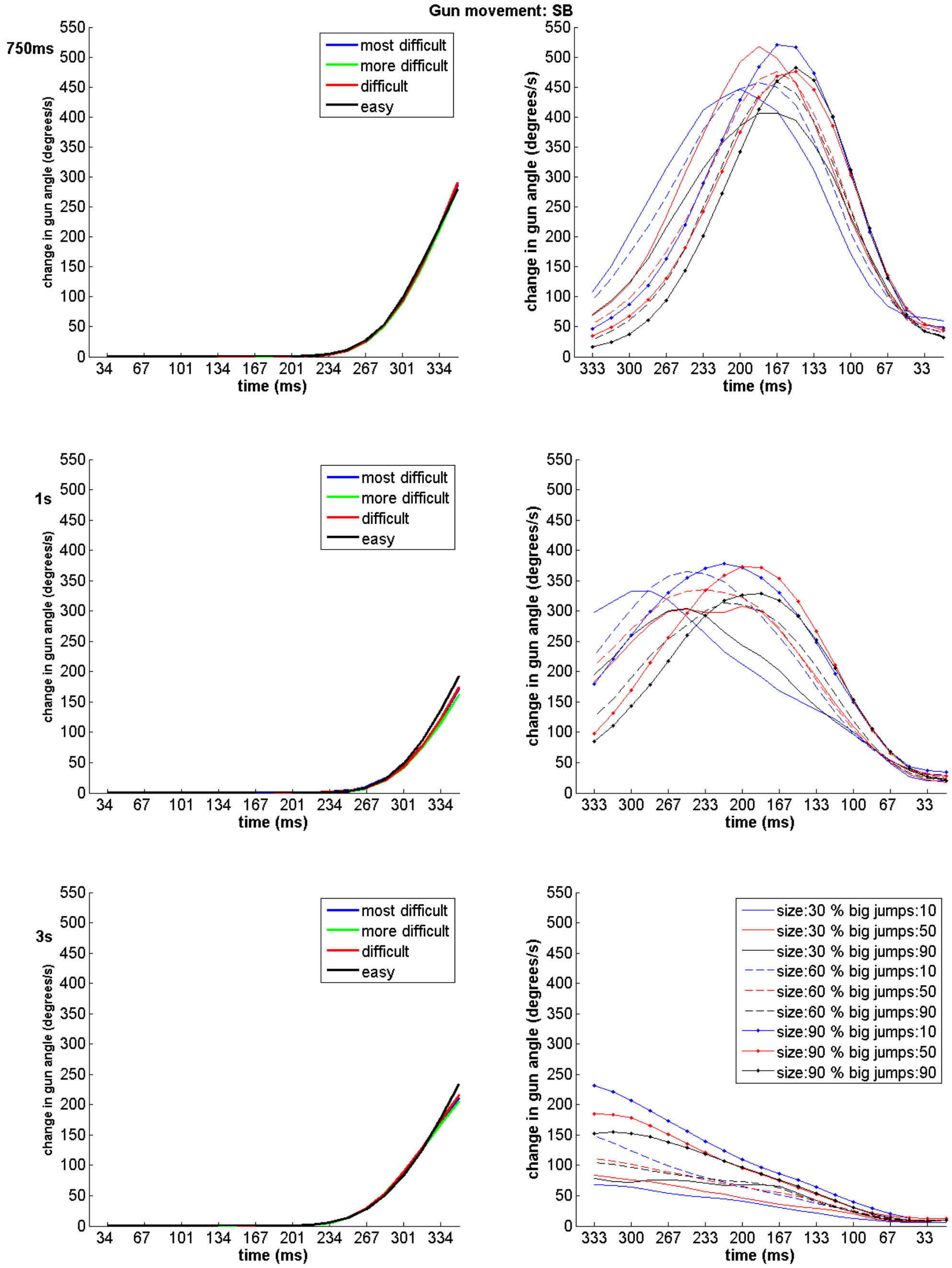

Figure 15. Gun velocities at different times in the trial for subject SB. Left side panels show gun velocities from the start of the trial until 333ms after the start of the trial. . Different lines represent trials with different levels of discriminability between target hit rates. Right side panels show gun velocities looking back 333ms from the time SB fired a shot. Different lines represent different target types. Different rows display data from different trial durations. All data are from two-target trials.

Time management

The subject's task had two parts. They had to decide which target to shoot at, and they had to aim and fire. This division requires that subjects balance their time. If they spend too long to decide they may end up rushing their shooting and performance will suffer. If they decide too quickly they may end up picking a target that is more difficult for them to hit, despite the extra time left for aiming. The following analyses first characterize what subjects did. Then two models are introduced: one that manages its time in a way that maximizes the expected probability of a hit; and another that manages its time in a way that minimizes expected shooting error. Finally, I will compare and contrast subjects' performance with each model.

In order to examine the effects of different trial durations in more detail, each trial was partitioned into a deciding and aiming+shooting phase. In order to do this, a gun velocity threshold was developed by visually inspecting gun velocities from dozens of individual trials for each subject. Once a velocity of 10 degrees/s was reached, a decision had been made. This threshold was chosen because velocities were always zero in the beginning of the trial for all subjects and this stable baseline made 10 degrees/s a consistently noticeable departure. Since it is not known exactly when the final decision about which target to shoot at has been made, this velocity threshold will be used to define movement latencies. These movement latencies are an estimate as to when the decision was made. This rests on the assumption that it is detrimental to the task to move the gun when it is not necessary to do so.

Thus, total trial time was partitioned into movement latency (time until the 10 deg/s threshold was reached) and aim+shoot time (total trial time – movement latency, where 'total trial time' refers to the time between the start of the trial and when they fired the gun). These times can be seen in Figure 16 for all subjects and trial durations. Figure 16, left side, shows that movement latencies increased with trial duration for two subjects (BF and JW). SB had a longer movement latency that remained about the same across durations. The decrease in movement latency from the longest to shortest trial durations was about 100 ms (25-30%) for BF and JW.

Figure 16, right side, shows large decreases (about 600 ms, >50%) in the time used to aim+shoot the gun as trial duration decreased. Figure 16 suggests that the time pressure of the short trials resulted in a greater proportional sacrifice of aiming+shooting time than decision time. For 2 of the 3 subjects, both aspects, deciding and aiming, were adjusted to take trial duration into account.

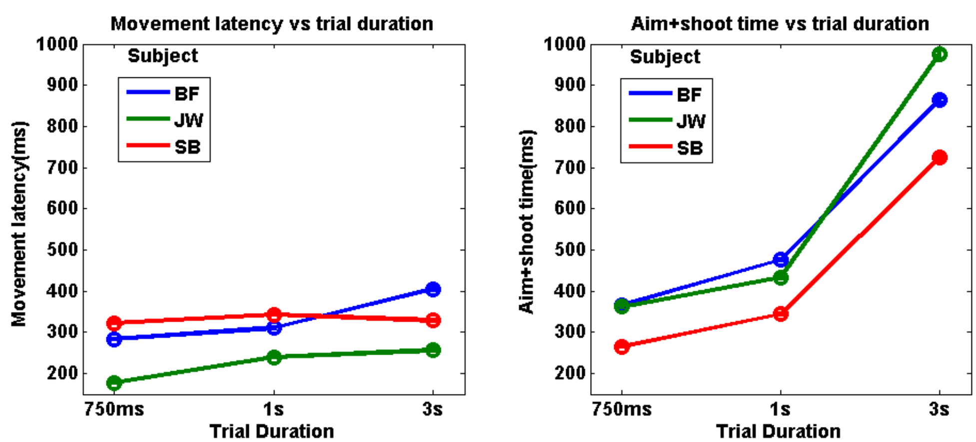

Figure 16. Movement latencies (left) and aim+shoot times (right), plotted as a function of trial duration. Different lines represent different subjects. Error bars indicate ± 1 s.e.

The use of a threshold gun velocity for defining a boundary between decision and aim times presupposes that subjects did not quickly aim at one target and then change their mind to shoot at the other target. There were, however, occasional cases in which subjects did change their mind. A subject was considered to have changed their mind if they moved the gun 50 angular degrees in one direction from the vertical starting position and then made a subsequent adjustment in the same trial that brought the gun 50 angular degrees in the opposite direction from the vertical starting position. Figure 17 shows the probability of each subject changing their mind as a function of trial duration. All subject's changed their mind more often in 3s trials compared to 750ms trials. All trials in which subjects changed their mind were removed from Figure 16 as well as from the following analysis on decision and aim times.

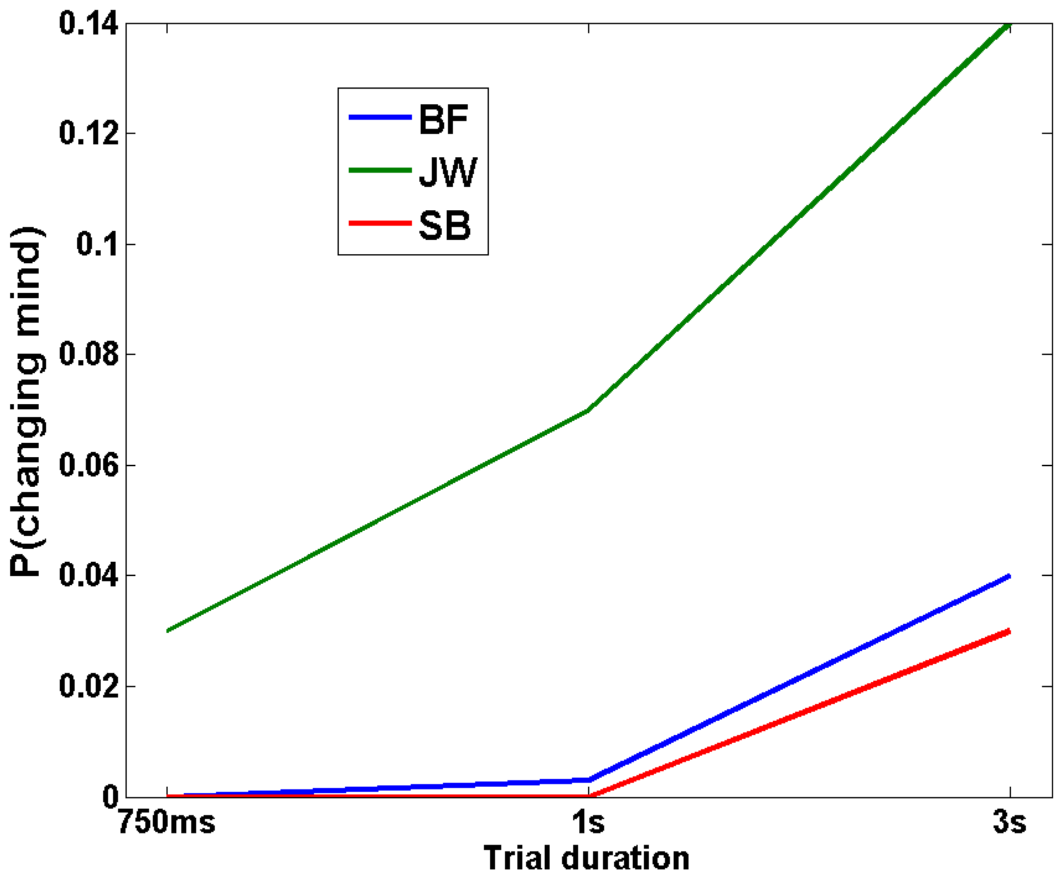

Figure 17. Probability of aiming at one target and then shooting at the other, plotted as a function of trial duration. Different lines represent different subjects.

Maximizing expected probability of a hit and minimizing expected error

In order to determine whether or not subjects' movement latencies and aim+shoot times maximized their expected chances of a hit, or minimized their expected shooting error, two models were developed. One model maximized the expected probability of a hit and the other minimized the expected magnitude of the shooting error. First, a logistic model was fit to the probability of choosing the easier target as a function of movement latency (Figure 18; top row). BF showed a slight decrease in their ability to detect the easier target as a function of time. JW and SB (not shown) showed the opposite. Second, a logistic model was fit to the probability of a hit as a function of aim+shoot time for each of the 9 (3 sizes x 3 probabilities of a big jump) target types (Figure 18; middle row shows a typically noisy fit). Lastly, a linear regression model was fit to shooting error as a function of aim+shoot time for each of the 9 target types (Figure 18; bottom row). Then, using these functions, the movement latencies and aim+shoot times that maximized E[*P(hit)*] and minimized E[*shooting error*] were computed for every trial for each subject. The expected probability of a hit for a given pair of movement latencies and aim+shoot times was computed as:

$$E[P(hit)] = P(t_1|\mathrm{ML}) * \mathrm{HR}(t_1|\mathrm{AT}) + P(t_2|\mathrm{ML}) * \mathrm{HR}(t_2|\mathrm{AT}) \qquad (1)$$

where $P(t_1|\mathrm{ML})$ is the probability of picking target 1 given the chosen movement latency (ML) and $P(t_2|\mathrm{ML}) = 1 - P(t_1|\mathrm{ML})$, and is taken from the function fit to the probability of choosing the easier target (always defined as t_1) as a function of movement latency for each subject. HR(t_1| AT) is the hit rate, as a percentage, for target 1 given the time allotted for aiming (AT) and HR(t_2| AT) is the same but for target 2. Both of these terms are computed from the function fit to *P(hit)* as a function of aim time for each subject.

$$E[\textit{shooting error}] = P(t_1|\text{ML}) * \text{SE}(t_1|\text{ AT}) + P(t_2|\text{ML}) * \text{SE}(t_2|\text{AT}) \qquad (2)$$

Expected shooting error (Eq. 2), E[*shooting error*], was computed in the same way as E[*P(hit)*] but replaced HR(t_1| AT) with SE(t_1| AT) which represents shooting error for target 1 given the time allotted for aiming. Shooting error given aim time was computed using the function fit to shooting error as a function of aim time for each subject.

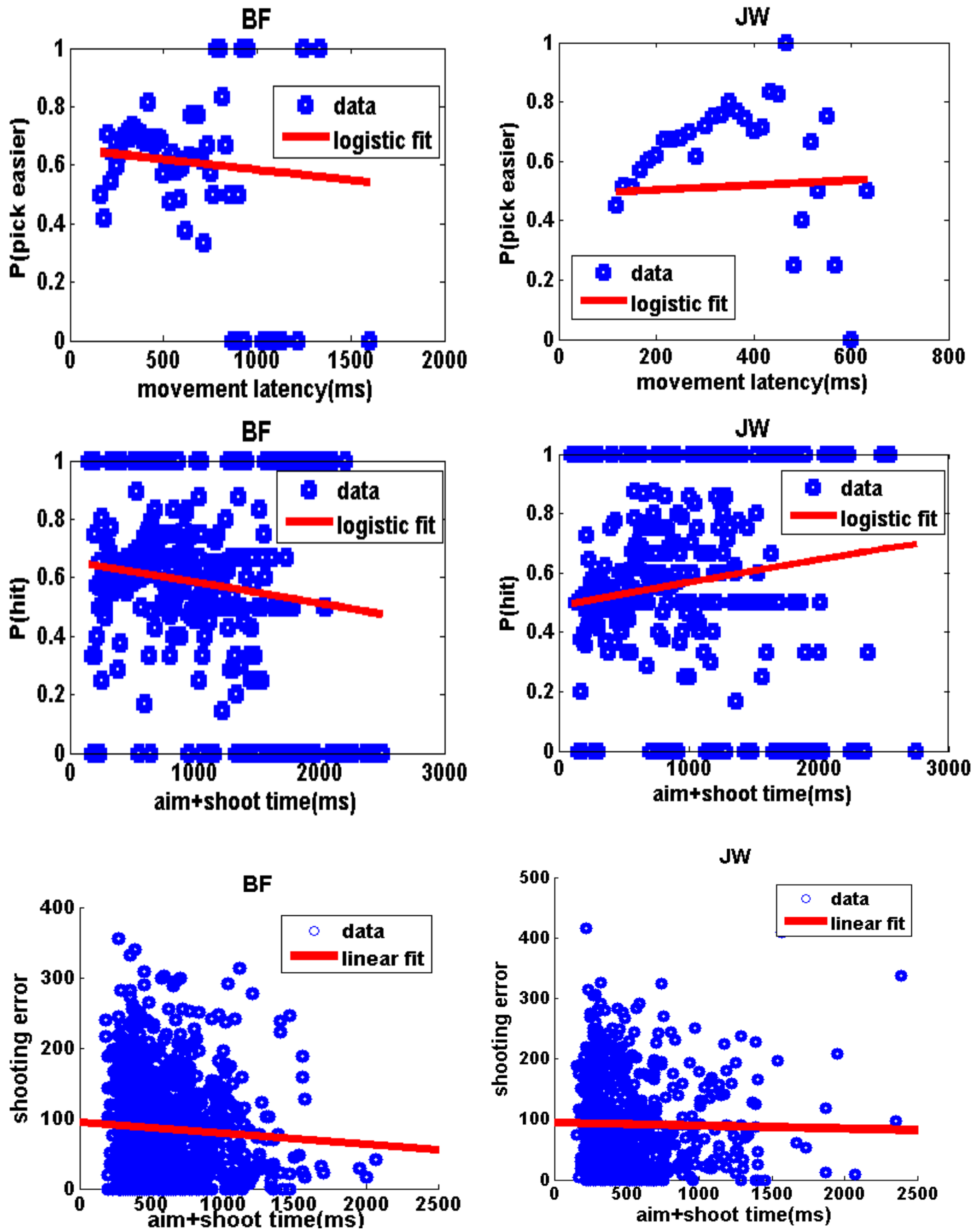

Figure 18. P(pick easier) plotted as a function of movement latency(top row) and P(hit) and shooting error plotted as a function of aim+shoot time(bottom two rows). Left column contains data for BF and right column contains data for JW. Blue points represent data from BF(top) and JW(bottom). Red lines represent logistic fits. Data are collapsed across all trial durations.

For every trial, E[*P(hit)*] and E[*shooting error*] were computed for each subject's movement latency and aim+shoot time. In addition, the pairs of times that maximized E[*P(hit)*] and minimized E[*shooting error*] on every trial were found via simulations that tried all possible pairs given the subject's reaction time for that trial. Furthermore, the max E[*P(hit)*] and min E[*shooting error*] were stored for every trial. A comparison of both models and subject's performance can be seen in Figures 19-21 for subjects BF, JW, and SB respectively. The top panels show E[*P(hit)*](left) and E[*shooting error*] (right), derived from the subjects' choice of decision and aim times. The bottom panels show performance for the models that maximized E[*P(hit)*](left) and minimized E[*shooting error*] (right). Mean (s.d.) and n can be seen for each set of data. By comparing mean performance derived from the data with that of the models it can be seen that all subjects underperformed both models, although not by much. Specifically, subjects chose movement latencies and aim+shoot times that led to a lower E[*P(hit)*] and a higher E[*shooting error*]. However it seemed subjects' performance was much closer to the model that maximized E[*P(hit)*] than to the model that minimized E[*shooting error*]. This is consistent with the instructions they were given (i.e. to "hit a target on every trial", *not* "try to hit the center of the target"). Overall these results suggest that subjects did fairly well, given the time they allotted to each trial. It is important to note that the model's selection of movement latencies and aim+shoot times was constrained by the subjects' reaction time rather than the total time available in the trial. This issue will be addressed in the General Discussion.

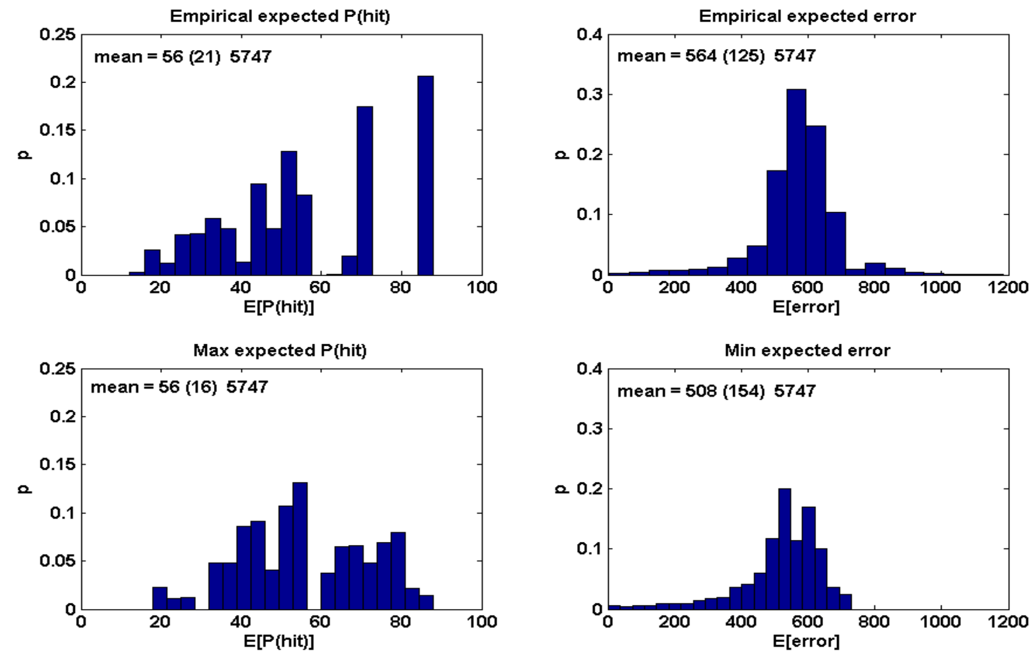

Figure 19. Histograms of expected P(hit) can be seen on the left for subject BF (top) and the model that maximizes expected P(hit) (bottom). Histograms of expected error can be seen on the right for subject BF (top) and the model that minimizes expected error (bottom). Each panel contains mean (s.d.) and n.

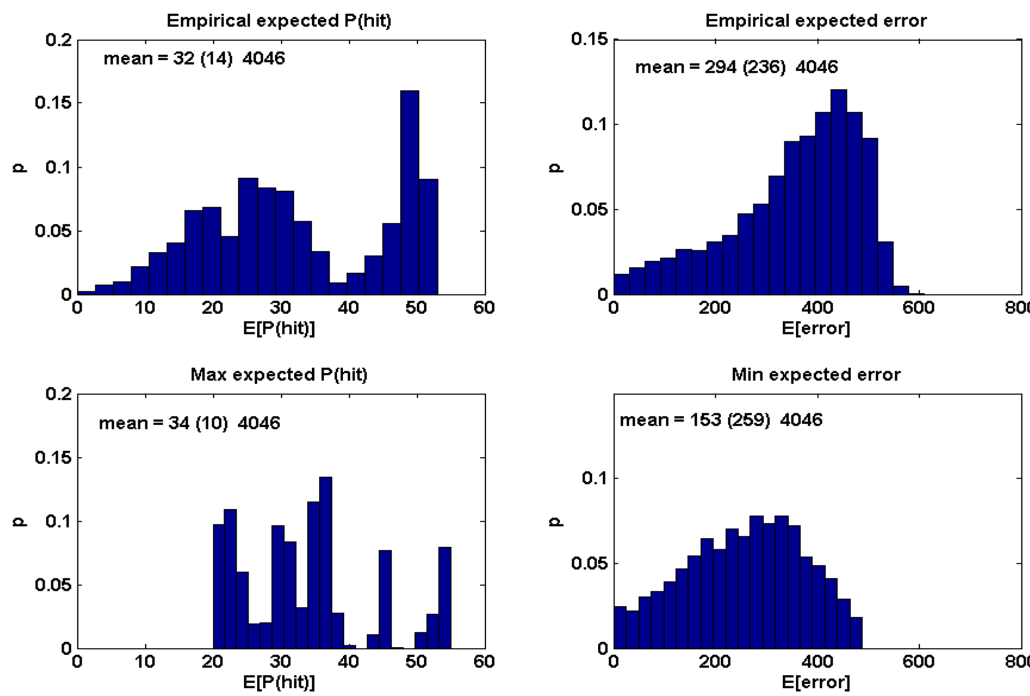

Figure 20. Histograms of expected P(hit) can be seen on the left for subject JW (top) and the model that maximizes expected P(hit) (bottom). Histograms of expected error can be seen on the right for subject JW (top) and the model that minimizes expected error (bottom). Each panel contains mean (s.d.) and n.

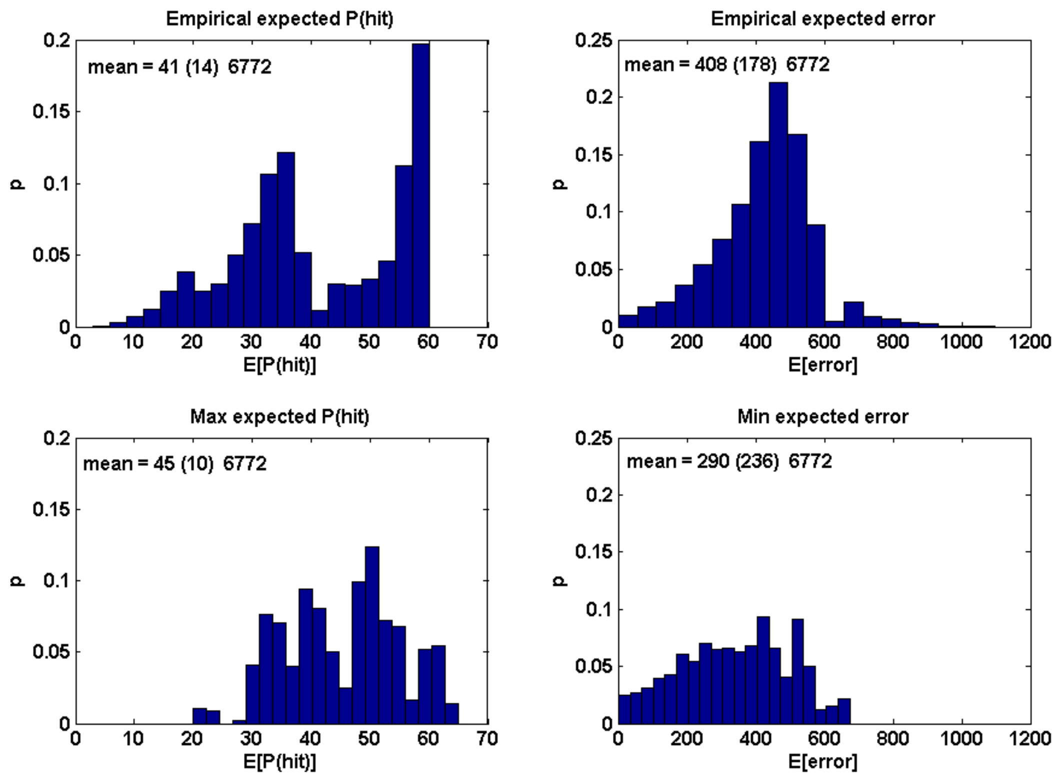

Figure 21. Histograms of expected P(hit) can be seen on the left for subject JW (top) and the model that maximizes expected P(hit) (bottom). Histograms of expected error can be seen on the right for subject JW (top) and the model that minimizes expected error (bottom). Each panel contains mean (s.d.) and n.

Shooting Early

Figure 9 shows that subjects rarely used more than 66% of the total trial duration when they were given 3s to decide and shoot. This seemed irrational, given that their discrimination and shooting performance both fell short of perfect. In order to determine if subjects' performance had reached an asymptote, cumulative P(picking easier target) was plotted as a function of movement latency (Figure 22;left column) and cumulative P(hit) was plotted as a function of aim+shoot time (Figure 22;right column). These data show that subjects were at asymptote rather early on in the trial. This suggests that the tendency to end the trial early did not have any detrimental effects on performance.

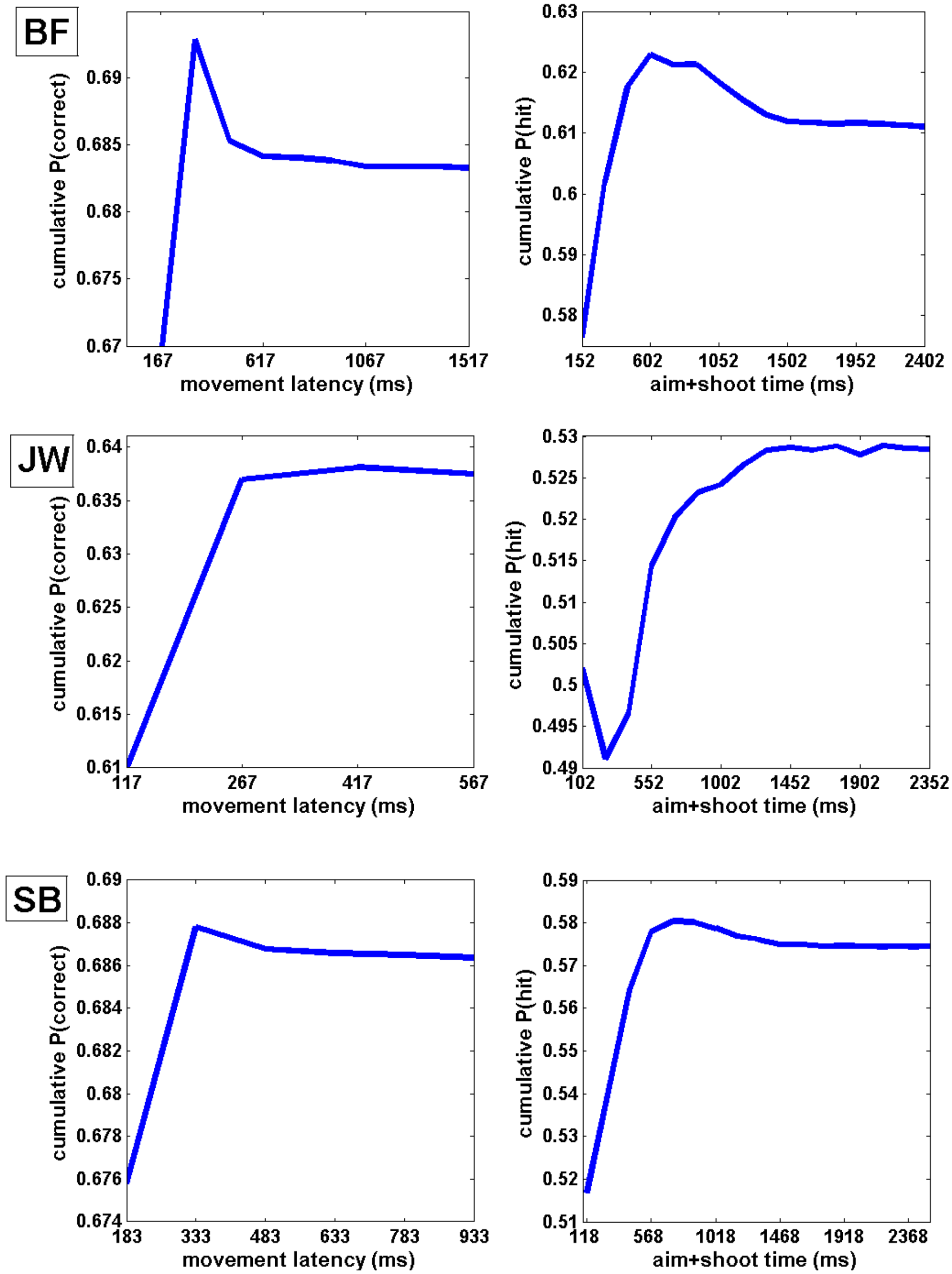

Figure 22. Cumulative P(correct) plotted as a function of movement latency (left column) and cumulative P(hit) plotted as a function of aim+shoot time (right column). Different rows represent different subjects. Data are pooled across all trial durations and conditions.

Learning

In order to determine whether subjects based their target choices on a learned association between feedback and target type, discrimination performance was examined by splitting the data into thirds. Then, for each set of trials, the probability of selecting the easier target was computed. These data can be seen in Figure 23. Figure 23 shows that subjects were equally good at choosing the easier target across the entire duration of the experiment. This suggests that their decisions were not based on gradual learning within the experiment itself.

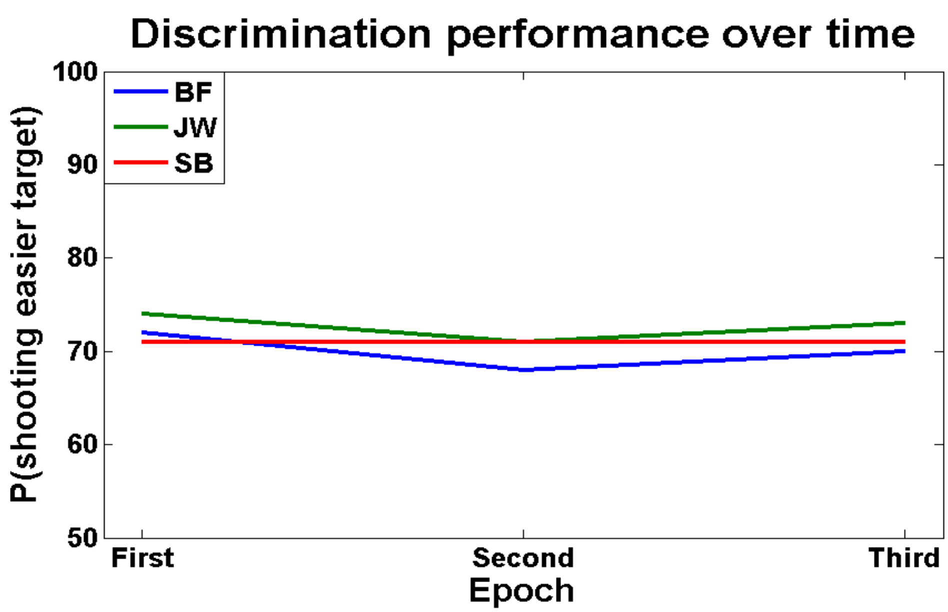

Figure 23.Discrimination performance plotted as a function of Experimental epoch (time), for all subjects.

Aiming strategies

In order to examine the impact of different aiming strategies on performance, two simulations were run. In one, the computer always shot at the current target position. This simulation consisted of 1000 trials with uniformly selected trigger times in the range [1333-1666ms]). By randomly selecting trigger times, the simulation ensured that the results were not merely a byproduct of timing the shooting in between position updates. The point of this simulation was to show the cost of bullet travel time. In other words, if subjects shot at current target position, the bullet would have to travel toward that position while the target could potentially move, depending on if this was a frame in which a position update occurred (6hz). Performance for this model can be seen in Figure 24(top). Shooting at the current target position results in performance that is markedly better than subject's shooting performance. Roughly the same effects of the two independent variables can also be seen in the top row of Figure 24. Namely that smaller targets that make more frequent big jumps are less likely to be hit than larger more stable targets.

A second simulation was run, where the computer shot at the 3rd most recent target position (Figure 24; bottom row). Performance was worst for this strategy than for aiming at current target position, although not by much. It is possible that the difference in position was often very little since positions were only updated at 6hz. This may be why the largest differences between the two simulations occurs at the highest probability of a big jump.

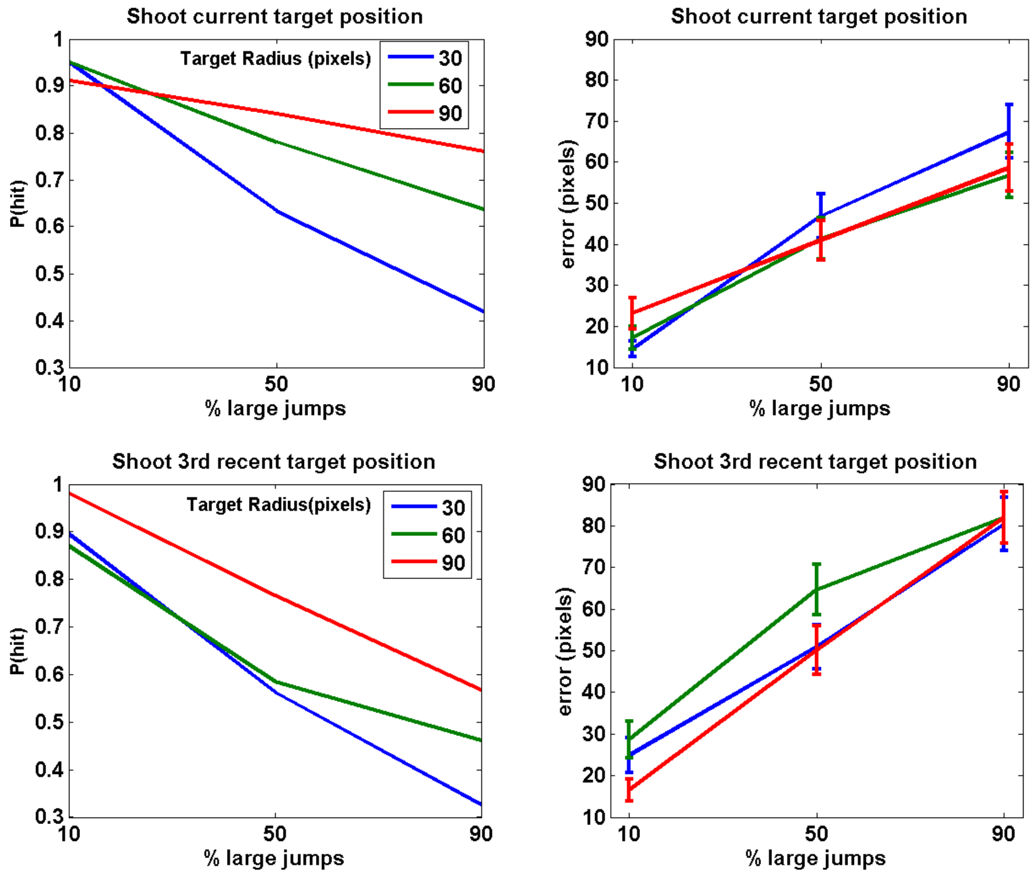

Figure 24. Simulated results for a strategy of shooting at the current target position (top) and shooting at the 3rd most recent target positions (bottom). On the left is P(hit) plotted as a function of probability of a big jump. Different functions represent different target sizes.

4. General Discussion

The present study examined visuomotor decision making under uncertainty and temporal pressure. The main questions were: (1) do subjects use internal performance estimates when selecting among a set of options in a visuomotor task?, (2) Do they split time efficiently between choosing the best option and executing a motor response?, (3) do heuristics exist in deciding which option is best?

Did subjects use internal performance estimates when selecting among a set of options in a visuomotor task?

In both experiments, subjects tended to shoot at the target that had a higher probability of a hit more than 70% of the time. In the first experiment, all single-target blocks were run before beginning the two-target blocks. This gave subjects hundreds of trials of experience and feedback from shooting at all the different target types. However in the second experiment, with 2 of 3 subjects who did not run in experiment 1, single- and two-target blocks were interleaved from the beginning. Despite the lack initial experience in Experiment 2, subjects' ability to determine the target with a higher hit rate was comparable to that found in Experiment 1. Furthermore, subjects' tendency to shoot at the target with a higher hit rate was stable across all sessions. This suggests that subjects were relying on internal estimates of motor performance that existed independently of their experience with this particular task. This is consistent with work from Trommershauser, Maloney, & Landy (2003) that found that subjects were able to optimally plan reaches based on knowledge of their own motor variability. The current result also agrees with work from Battaglia & Schrater (2007), who found that subjects performed a timed visuomotor task equally well with and without feedback.

Did subjects split time efficiently between choosing the best option and executing a motor response?

Data from experiment 2 showed that subjects' decision and aim times resulted in performance that was very close to that predicted by two different models: one that selected decision and aim times to maximize the expected probability of a hit and one that selected decision and aim times to minimize the magnitude of expected shooting error. The predictions of both models took into account the effects of time, so that the ability of subjects to approximate the predicted performance argues that subjects were able to use available time efficiently. In the present task, using time efficiently was a challenge because it was necessary to apportion time between two very different and time-consuming aspects of the task: deciding which target to shoot, and carrying out the process of aiming and shooting. However, subjects did slightly underperform both of these models. The underperformance may have been due to a number of factors. First, subjects tended to rely too heavily on size when deciding which target to shoot at. This may have led to shorter decision times than were required to maximize the expected probability of a hit. This is an issue that will be addressed in the next section in more detail.

Experiment 2 also showed that subjects tended to increase the time devoted to aiming much more than the time devoted to deciding which target to shoot as trial duration increased. The modest increases in decision times may have been due to an overreliance on size. Size discrimination is a very fast process and may have been used to choose which target to shoot at. If that were the case, one would not expect large changes in decision time, since size discrimination was equally easy at all trial durations. Instead subjects left more time for aiming. Subjects may have used the additional aim time to avoid large jumps in target position by waiting for a jump to occur, and then firing at the target, once it reached it's new location. This is a strategy that's not possible at shorter trial durations. However, given how well the model captured performance it is likely that the decisions about apportioning time were in fact close to the best that could have been made. It is interesting that people can fine-tune timing strategies to approach best possible performance. In addition, results showed that subjects asymptoted quickly and the fact that they tended to not use all of the available time suggests that they were aware of this.

Do heuristics exist in deciding which option is best?

Across both experiments, there was a tendency to rely too heavily on size when deciding which target to shoot. This tendency was weaker when subjects were given more time but was still present. This overreliance on size may have been a reasonable strategy given the time limits. Size is more readily available perceptually than constant velocity, from Experiment 1, or the probability of a big jump, from Experiment 2; both of which require multiple frames to determine. In addition, size had a bigger effect on shooting performance. Together, these two reasons may explain why subjects relied more on size and why this heuristic was more common at shorter trial durations.

Conclusion

The current work extends findings from previous studies by showing that visuomotor decision making in the presence of uncertainty and urgency is quite good, even in a task that is far more complicated than those used in prior work on this subject. For instance, Trommershauser, Maloney, & Landy (2003) and Battaglia & Schrater (2007) used tasks in which subjects had to reach to a single goal before a deadline. In the current study there are two potential targets that must be evaluated along 2 dimensions before initiating a motor response. In addition to evaluating the targets, time must also be taken into consideration in order to fire at the desired target before the deadline.

Battaglia & Schrater (2007) demonstrated that subjects' use of internal estimates of motor performance was sensitive to the effects of time. However in the current study, subjects needed to understand how two different variables, namely size and motion pattern, interact with time to determine shooting performance. This estimate had to then be used in the perceptual part of the task; deciding which target to shoot at. This adds an additional layer of complexity that makes the current task more similar to natural tasks (e.g. driving) that often require the evaluation of multiple targets along many dimensions and carry important consequences for bad timing. Adjustments made to decision and aim+shoot times reflect an overall understanding of how time affects the decision and the motor phases of the task.

In conclusion, the current study demonstrates that internal estimates of motor performance, conditioned on visual information and urgency, are used in deciding between options in a timed visuomotor task. Subjects tended to split their time between deciding and aiming in a way that brought their performance close to models that maximized expected probability of a hit and minimized shooting error. In addition, urgency led to the use of a heuristic, namely shooting at the larger target, which simplified the decision process without having too detrimental an effect on the overall task goal; hitting a target on every trial. Together, these results show that visuomotor decisions are controlled by a complex interaction between external factors, such as the physical characteristics of the options that are available, and internal factors, such as an estimate of motor ability that is sensitive to the effects of rushing the motor response.

Visuomotor tasks in everyday life often confront people with the need to choose among available targets and to determine how much time to devote to different aspects of perceptual analysis or motor preparation. In the case of high speed tasks in real environments – driving or real (rather than virtual) shooting, for example – the consequences of mistakes can be severe. The excellent performance of subjects in the present experiment raises interesting questions. First, how do people learn the strategies that optimize performance? Are there built in rules or is only a relatively brief exposure to task outcomes required (the results of experiment 2 showed no benefits of long-term learning)? Second, what are the limits of performance? The present tasks were chosen because of their apparent difficulty and yet subjects did quite well at adopting excellent strategies. It is important for understanding real-world activities and their neural basis to find the conditions under which the excellent abilities demonstrated here will break down. Factors such as the number of target alternatives, the similarity of the alternatives, the extent of prior experience, the presence of time limits, etc., may all prove essential. The role of such factors in perceptual and cognitive performance (memory, decision-making) are typically studied in fairly constrained laboratory tasks. The present study provides a platform to find out how capacities are put to use in demanding active visuomotor task environments.

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