INTERCEPTING MOVING TARGETS:
A LITTLE FORESIGHT HELPS A LOT

by

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ABSTRACT

Behavioral studies suggest that humans intercept moving targets by maintaining a constant bearing angle (CBA). The purely feedback-driven CBA strategy has been contrasted with the strategy of predicting the eventual time and location of the future interception point. This study considers an intermediate strategy involving prospective control based upon a prediction of the state of the bearing angle a short duration into the future. Subjects sat in front of a large projection screen and watched computer generated displays that simulated linear self-motion over a textured ground plane. Simulated speed was controlled by adjusting a foot pedal, the position of which was mapped onto speed according to a first-order lag. Subjects were instructed to intercept spherical targets as they moved across the ground plane. When targets changed speed midway through the trial in Experiment 1, subjects abandoned an unsuccessful CBA strategy in favor of a strategy involving the prediction of the most likely change in target speed. In Experiment 2, targets followed paths of varying curvature. Subject behavior was inconsistent with both the CBA and the purely predictive strategy. To investigate intermediate strategies, human performance was compared with a model of interceptive behavior that, at each time-step t, produced the velocity adjustment that would minimize the change in bearing angle at time $t+\Delta t$, taking into account the target's behavior during that interval. Values of Δt at which the model best fit the human data for practiced subjects varied between 0.25 s and 1.5 s, suggesting that subjects adjusted velocity to keep the bearing angle constant a short time into the future.

1. Introduction

Humans and non-human animals demonstrate the capacity to perform a running interception of a target moving across the ground plane in a variety of contexts. Because of this fundamental involvement in perceptual-motor behavior, strategies of locomotive interception have long been the subject of study. However, a surprisingly small portion of this research has acknowledged that many creatures, ranging from predators in the wild to humans on the playing field, repeatedly demonstrate the capacity to intercept targets that change speeds and directions in unpredictable ways. In this study, I first re-evaluate previous models that were designed to explain the interception of constant velocity targets within a somewhat more realistic context that involves changing velocity targets. Two experiments were conducted to investigate human behavior in this situation. In Experiment 1, subjects were tested for the ability to accurately anticipate probable changes in the target's velocity. In Experiment 2, subjects were presented with targets that approached along either a rectilinear path or one of several possible curved trajectories. Subjects' behavior was compared against that of an ideal pursuer that accurately positions itself in anticipation of the expected target position and velocity a brief period into the future. The degree of similarity between subjects' behavior and the ideal pursuer's behavior provided an indication of subjects' ability to act so as to bring about a desired future state that is dependant upon accurate anticipation of the target's dynamics.

Situations involving moving targets that change velocity can often be observed in a game of American football. In football, it is often necessary for a defender to approach and intercept a ball carrier on the opposing team as the ball carrier tries to evade the defender (Figure 1). The defender's task is complicated by the possibility of unpredictable changes in the speed and direction of the ball carrier's motion. An experienced defenseman might orient his approach in anticipation of these changes and in such a way that limits the ball carrier's chances of evasion. In other words, the ideal approach would account not just for current target behavior, but also for the possible changes in behavior.

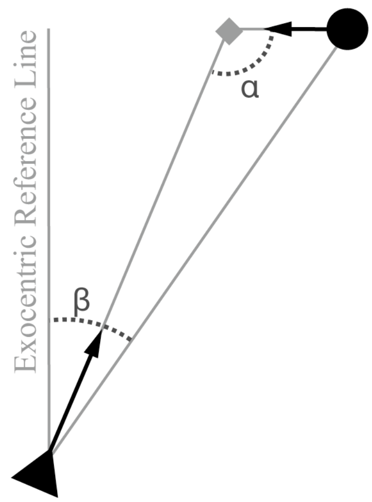

Figure 1: An overhead view of an exemplary interception situation. The pursuer (triangle) and target (circle) approach the invisible interception point (diamond). β denotes bearing angle and α denotes the target's approach angle.

1.1 A Brief History of Locomotive Interception

1.1.1 The Constant Bearing Angle Model

The most widely accepted model of locomotive interception was originally a strategy that has been used for centuries by sailors to avoid collisions with nearby vessels (Le Brun 2002). Known amongst scientists as the constant bearing angle (CBA) model of interception, the strategy proposes that by maintaining a constant bearing angle the observer is guaranteed to intercept the moving target. The bearing angle (β) is the direction of the target with respect to an exocentric reference line (see Figure 1). An increasing bearing angle suggests that the observer will pass in front of the target and that it is necessary to decelerate or turn toward the target for a successful interception. A decreasing bearing angle suggests that the observer will pass behind the target, and that it is necessary to accelerate or turn ahead of the target for a successful interception. Empirical tests have demonstrated behavior consistent with the CBA model when making passive judgments of an impending collision (Cutting et al. 1995). In addition, the model has been shown to provide an account of the active interception strategies in both humans and of several non-human organisms including dragonflies (Olberg et al. 2000) and teleost fish (Lanchester and Mark 1975). The CBA model of interception has also been suggested as a potential control law for guiding lateral movements when running to catch a fly ball (Chapman 1968).

The first data to suggest that humans use a bearing angle strategy while intercepting a moving target were reported by Lenoir and colleagues (Lenoir et al. 1999a; Lenoir et al. 1999b). Subjects were asked to hit a target moving along a track by controlling the speed of their approach on a tricycle. Subjects' heading was fixed. Though results were consistent with the CBA model, technical limitations may have oversimplified the task and resulting behavior. The target's movement was restricted to one approach angle, and the target moved at one of only two possible constant velocities. Each velocity was presented ten times for a total of twenty trials of limited variety. This simplicity of design may have allowed for behavior stereotyping in response to the observed speed. Furthermore, target motion started only after the observer was a short fixed distance from the interception point. This only allowed for an analysis of the final seconds of approach. Thus, although the data suggests use of the CBA strategy, the findings were far from conclusive due to methodological limitations.

Since then, more convincing support for the CBA model has been provided. Behavior consistent with the CBA model has been shown in a less constrained and more natural environment by asking subjects to move about freely and intercept a soccer ball (Lenoir et al. 2002). Chardenon et al. found that subjects conform to predictions generated by simulations of the bearing angle as an actor walked at constant velocity: larger initial approach angles were accompanied by larger changes in bearing angle, and thus more pronounced velocity adjustments during the subject's approach (Chardenon et al. 2005). Another experiment utilized targets that approached along curvilinear paths (Bastin et al. 2006b). Strong evidence for a CBA strategy was provided on trials in which no velocity adjustments were necessary for a successful interception. No velocity adjustments were necessary on such trials (a subset of all trials) because when the target first appeared, subjects were already moving at the speed that would eventually bring them to the interception point at the same time as the target. Though it was not necessary for a successful interception, subjects regulated their velocity on the basis of changes in bearing angle that resulted from the target's curvilinear approach. These velocity regulations fit qualitative predictions of the direction and magnitude of the subjects' initial and subsequent velocity adjustments. Furthermore, regression analyses based upon the CBA strategy were able to explain an average of 56% of the total variance at the trial level, and 75% of the total variance at the group level, after the data has been averaged across trials and subjects.

Another line of research focuses on the informational basis for perceiving the bearing angle. Bastin and Montagne (2005) suggested that the informational basis for the perception of bearing angle is likely a combination of variables that is highly dependent upon the structure of the environment. Though optic flow has been suggested as a potential influence on interception strategies (Chardenon et al. 2005), the manipulation of optic flow has been shown to have only a minor effect upon behavior (Fajen and Warren 2004). The manipulation of proprioceptive information suggests that it is utilized in both the perception of the bearing angle as well as for the regulation of velocity adjustments during interception (Bastin et al. 2006a). Furthermore, simulations by Fajen and Warren (2007) demonstrated that the bearing angle whose change is nulled must be defined in an exocentric reference frame. When simulated agents keep the target at a constant egocentric (rather than exocentric) direction, under certain conditions the resulting trajectory spirals behind the moving target, unlike human subjects who follow a straight path ahead of the target. The implication for the informational basis of interception is that the influence of observer rotation on the change in target-heading angle must be factored out. In principle, this could be achieved using visual, vestibular, or podokinetic information.

1.1.2 The Required Velocity Model

Another proposed model of interception behavior, the Required Velocity Model, was initially suggested as a model of guiding hand movements when catching a ball passing by within reach (Peper et al. 1994; Bootsma et al. 1997). Within this context, the RV is the lateral distance between the ball and the hand divided by the amount of time until the ball will reach the hand. The model proposes that, if the hand continuously travels towards the current lateral position of the ball at the speed specified by the RV, both the target and the hand will arrive at the point of interception at the same time. Optically, the ball's future passing distance is specified in units of ball size by the ratio of the lateral velocity of the center of expansion over the rate of expansion of the ball (Peper et al. 1994). More recent experiments have found that different individuals may rely upon different optical variables for the perception of RV, and that the variables relied upon may be influenced by experience (Jacobs and Michaels 2006).

In accordance with the model's predictions, research has demonstrated that changes in the target's speed or initial distance do not affect behavior when the time until the ball will reach the hand is held constant (Montagne et al. 2000). In addition, predictions of reversals in the direction of hand movements match the observed behavior (Montagne et al. 1999). However, more recent research has drawn attention to the model's inability to account for particular aspects of hand movements, such as consistent overshoots past the interception point (Dessing et al. 20002).

Within the context of interception involving whole body displacements, the RV is the constant subject velocity that would cause the subject to collide with the target. Thus, if the subject maintains a constant heading, the RV is the ratio of the subject's distance from the interception point, where the target intersects the subject's path of motion, to the time until the target arrives at the interception point. The model suggests that a subject can intercept a target by equalizing his or her current velocity with the required velocity. This differs from predictions made by the CBA model in that the RV model uniquely predicts consistent behavior across any trial in which the target's arrival time at the interception point is consistent. It follows that the RV model predicts that behavior is independent of changes in the angle from which the target approaches.

Despite its validity as a potential interception strategy, there does not seem to be a strong empirical basis for use of the RV in interception. Initial studies found that the RV model could not explain subjects' early velocity regulations (Chardenon et al. 2002). Multiple linear regressions were run across 240 trials at one-second intervals during the last six seconds of the subjects' approach to the target. The RV model could account for only 8.5% of the velocity regulations at 6 seconds before contact and, though the effect strengthened as the observer neared the target, the RV model could at best account for 46% of the variability in the subjects' velocity regulations at 1 second before contact. Though it was suggested that the RV model might play a role later in the subject's approach, it does not seem to provide a good account of the majority of subject behavior.

1.2 Interception strategies in the presence of variability

Unlike the experimental conditions in which the CBA and RV models have been tested, real world conditions are subject to sources of variability that may complicate behavior. Further, although interception is guaranteed once a CBA or the RV has been achieved within these idealized experimental conditions, this is not necessarily the case in the presence of variability. This is a symptom of a general problem: neither the CBA model nor the RV model can explain how actors take into account the consequences of variability.

In an interception task, variability may arise from unpredictable changes in target velocity. For the purposes of illustration, consider the (admittedly unrealistic) situation in which the target changes speed in a predictable manner across trials. In other words, at the beginning of each trial the target moves along the same trajectory at the same initial speed as on every other trial, and then changes its speed by the same magnitude at the same point in time as on every other trial. It will also be assumed that the pursuer can adjust speed but not heading. (In Experiment 1, subjects are presented with a more realistic situation in which targets change speeds by an amount that randomly varies from trial to trial, but with some statistical regularity.)

One would expect that, contrary to the predictions of the CBA or RV models of interception, a human pursuer would eventually learn to anticipate the target's predictable increase in speed. A pursuer with accurate expectations of the target's acceleration could make anticipatory speed adjustments before the change in target speed that would bring about the desired state (a CBA or RV) immediately following the change in target speed.

1.2.1 Using TTC to compare strategies

By how much should the pursuer change her own speed in anticipation of the change in target speed to maximize her chances of intercepting the target? In this section, I will present a method for predicting the ideal speed change in the context of the simplified example of a target that always accelerates by the same amount. In the next section, this method will be extended to the more realistic situation used in Experiment 1. It should be emphasized that this method is not intended to be a possible control strategy used by human actors, as it assumes knowledge that humans are not likely to have when intercepting targets. Rather, the method is used for generating predictions about behavior for an ideal pursuer.

Recall that, in the simple example presented earlier, a predictable fixed-heading target increases speed by the same magnitude at the same time on each trial. Further, the subject is constrained to movement in a single dimension such that speed but not direction can be adjusted. Because both target heading and subject heading are fixed, the point of interception can be identified in advance. I define the target's *first-order time-to-contact* (*TTC*) as the amount of time it would take for the target to reach the interception point assuming that it does not change speed. Before the pursuer has enough experience to realize that the target always accelerates, it is expected that the pursuer will adjust speed in such a way that his or her first-order TTC will equal the target's first-order TTC. Such behavior would result from maintaining a CBA.

If the target accelerates, then the target's *actual TTC* with the interception point would be less than the first-order TTC. If the pursuer can perfectly anticipate the increase in target speed, then she should adjust her speed so that her TTC with the interception point equals the target's actual TTC with the interception point. (The reader is reminded that this is merely a description of behavior, and is not intended to be a possible underlying control strategy.) Once the pursuer's TTC is equal to the target's actual TTC, the pursuer can simply maintain speed to intercept the target.

By comparing the pursuer's TTC with the actual and first-order target TTC, I can determine the degree to which subjects can anticipate changes in target speed. If subjects can perfectly anticipate changes in target speed, then their TTC at the moment that the target changes speed should equal the target's actual TTC at that moment. On the other hand, if subjects cannot anticipate the change in target speed, then their TTC will be biased toward the first-order TTC.

2. Experiment 1: Anticipating Changes in Target Speed

In the previous example, the simplifying assumption was made that the target always accelerated by the same amount at the same time. In Experiment 1, I investigated whether subjects can anticipate changes in target speed in a more realistic situation in which the target changes speed by an amount that varies from trial to trial. A spherical target approached the interception point from one of three angles at one of three initial speeds. Between 2.5 and 3.25 s after the trial began, target speed changed to a final speed that was randomly selected from a normal distribution. Because the mean of the final speed distribution was greater than all three initial speeds, the target usually accelerated. However, the variance of the distribution was large enough that the target occasionally decelerated to its final speed.

When the change in target speed is unpredictable as in Experiment 1, the pursuer cannot perfectly anticipate the change in speed on every trial. The best the pursuer can possibly do is to anticipate the most likely change in speed; that is, adjust speed so that TTC is equal to the actual TTC of a target that changes speeds to the most probable final speed at the most probable time. So the goal of Experiment 1 was to determine if subjects can learn to anticipate the timing and magnitude of the most likely change in target speed.

2.1 Methods

2.1.1 Participants

Twelve undergraduate students from Rensselaer Polytechnic Institute participated in the experiment. Each had normal or corrected-to-normal vision.

2.1.2 Displays and Apparatus

A Dell Precision 530 Workstation with a 1.7 GHz Intel Xeon processor and an nVidia Quadro2 Pro graphics card generated the experimental stimuli and recorded the position and velocity of the subject and target at 60 hz. The stimuli were rear-projected via a Barco Cine 8 projector at a resolution of 1280 x 1024 onto a 1.8 m x 1.2 m screen at 60 hz. To reduce the salience of the screen frame, black felt covered the border of the frame and the surrounding walls. Participants viewed the stimuli from a distance of approximately 1m using unrestricted binocular vision of the monocular display.

Displays simulated the observer's movement at 1.1 m over a ground plane along a fixed path. The ground texture resembled a green grass covered field that is free of distinguishing landmarks, and the simulated sky was light blue. At the beginning of each trial, a moving target with a radius of .35 m approached the observer's path of motion from the right side (see Figure 2).

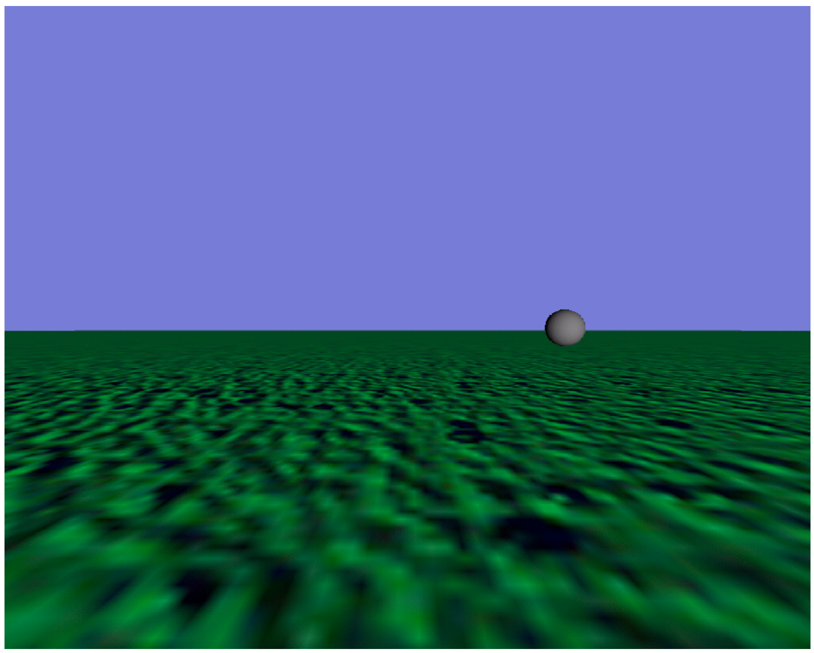

Figure 2: A sample frame of the experimental stimulus

The simulated target approached the unmarked interception point from an initial distance of 45 m, along an initial approach angle of 135°, 140°, or 145° from the subject's path of motion (α in Figure 1). The target traveled along a fixed path at one of three initial speeds 11.25 m/s, 9.47 m/s, 8.18 m/s, which correspond to initial first order time-to-contact values of 4 s, 4.75 s, and 5.5 s. At a randomly selected time between 2.5 and 3.25 s after the start of the trial the target gradually changed speed to a new value that was selected from Gaussian distribution. Final target speed was independent of initial target speed. The mean of the final target speed distribution was 15 m/s, and the standard deviation was 5 m/s. The range of the distribution was truncated to exclude speeds that lay farther than one standard deviation from the mean. The target changed speed at a constant rate over a duration of 0.5 s.

Subjects controlled their simulated speed using an ECCI Trackstar 6000 spring-loaded foot pedal. To begin each trial, subjects completely released the foot pedal and pressed a button. Initial distance from the unmarked interception point was randomized between 25m and 30m. Subjects' velocity had a lagged first-order relationship with the pedal position, defined by the equation:

$$\dot{V} = K * (V_p - V_s) \tag{1}$$

where V_p is the speed specified by the current pedal position, V_s is the subject's current velocity, and K is a constant lag coefficient. The lag coefficient was set to .017 because it produces a smooth relationship between the pedal movements and the resultant velocity changes, while still allowing the responsiveness needed for a successful interception. The range of possible speeds extended from 0 m/s to 14 m/s.

To successfully intercept the target, the subject had to pass within a distance of .35 meters from the center of the target.

2.2 Procedure

Upon arriving at the lab area, each subject provided written consent and was asked to read a set of instructions. The subject was then brought into the experimentation room and seated in a chair approximately 1 m from the projection screen. Eyeheight was approximately 1.1 m, equal to the simulated eyeheight used in the stimuli. The location of the foot pedal unit was manually adjusted to ensure comfort during participation.

Prior to the experiment, subjects completed a short practice session. During the practice session, each possible combination of initial approach angle and initial target speed was presented once, producing a total of 9 practice trials. During the experimental session, each combination was presented ten times within each of four blocks. The 3 (initial approach angles) x 3 (initial target speeds) x 10 (repetitions) x 4 (block) design produced a total of 360 trials during the experimental session.

2.3 Results and Discussion

2.3.1 Task Performance

The mean hit rate across all subjects and all four blocks was 47% (SD = 11.31). However, one subject's performance was particularly poor. Because his mean hit rate of 20% was 2.39 standard deviations below the group mean, he was treated as an outlier and his data were excluded from further analysis.

The 11 remaining subjects had a hit rate of 39.1% in block 1, but improved over blocks up to 54.9% in the final block (Figure 3). This steadily improving hit rate was mirrored by a steady decrease in the percentage of misses with the target passing in front. The percentage of misses with the target passing behind the subject was fairly constant and relatively low. This may be due to the fact that the target usually increased (rather than decreased) speed, but may also reflect a bias to keep the target within the ~80 degree field of view provided by the projection screen for as long as possible. A Chi-squared test confirmed the significant effect of block on the distribution of trial outcomes $X^2(6,N=3960)=57.00$, $p \leq .001$.

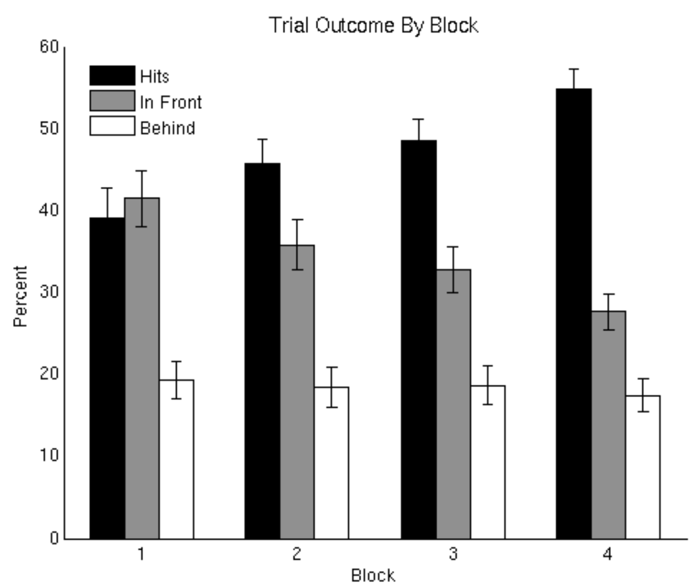

Figure 3: Proportion of each trial outcome by block in Experiment 1.

2.3.2 Did subjects use a constant bearing angle strategy?

The remaining analyses were based on measurements taken at the onset of the target's change in speed. The assumption is that in the 2.5 to 3.25 s before onset subjects will have had sufficient time to modulate their approach speed in anticipation of the target's change in speed. The first analysis will provide a test of the constant bearing angle strategy. If subjects used a constant bearing angle strategy, then the change in bearing angle at onset should be close to zero. However, t-tests revealed that the rate of change of bearing angle at onset was statistically different from zero on all four blocks $t(10)$=7.22, 9.47, 9.91, and 13.54, respectively, with $p \leq .001$ for each individual t-test (Figure 4). Although the change in bearing angle did not significantly differ from zero in some conditions, there was a consistent trend for the rate of change in bearing angle to grow with approach angle.

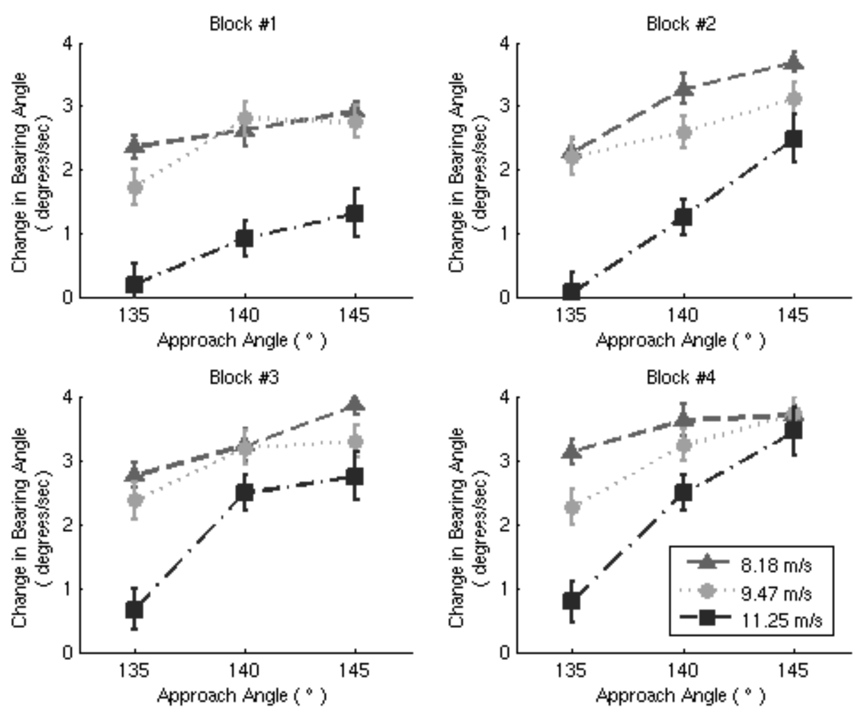

Figure 4: Change in bearing angle at onset by initial target speed, approach angle, and block.

Furthermore, if subjects were using a CBA strategy, then the subjects' TTC should match the target's first-order TTC at onset. This was clearly not the case (Figure 5), as subject TTC was consistently less than the target's first-order TTC. This was confirmed by calculating the difference between the subject's TTC and the target's first-order TTC on each trial, and then running t-tests for each of the 36 conditions (3 initial speeds x 3 approach angles x 4 blocks). Of the 36 t-tests used to test for a statistically significant difference between the subject's TTC and the target's first-order TTC, 30 t-tests show a significant difference from zero[1]. The results are included in Appendix 1.

To summarize, there was no evidence that subjects were trying to maintain a constant bearing angle during the first part of the trial. The change in bearing angle was consistently greater than zero and subject TTC was consistently less than the target's first-order TTC, suggesting that subjects anticipated the likely increase in target speed.

2.3.3 Did subjects use a predictive strategy?

If subjects modulated speed in anticipation of the most likely change in target speed, then the subject TTC should match the target's mean actual TTC. Visual inspection of Figure 5 suggests that, for the majority of initial conditions, the subjects' TTC was more similar to the target's mean actual TTC than the first-order target TTC. This observation is strengthened when one compares the frequency with which the subject TTC is statistically significant different from first-order TTC (30 of 36 t-tests, see section 2.3.2), and mean actual TTC (18 of 36 t-tests, see Appendix 2).

[1] Although alpha is often decreased to compensate for the greater family-wise probability of a type 1 error when performing multiple t-tests, my strategy of maintaining an alpha of 0.05 was the more conservative approach in that it increased the odds of failing to reject the null hypothesis when we should actually reject it.

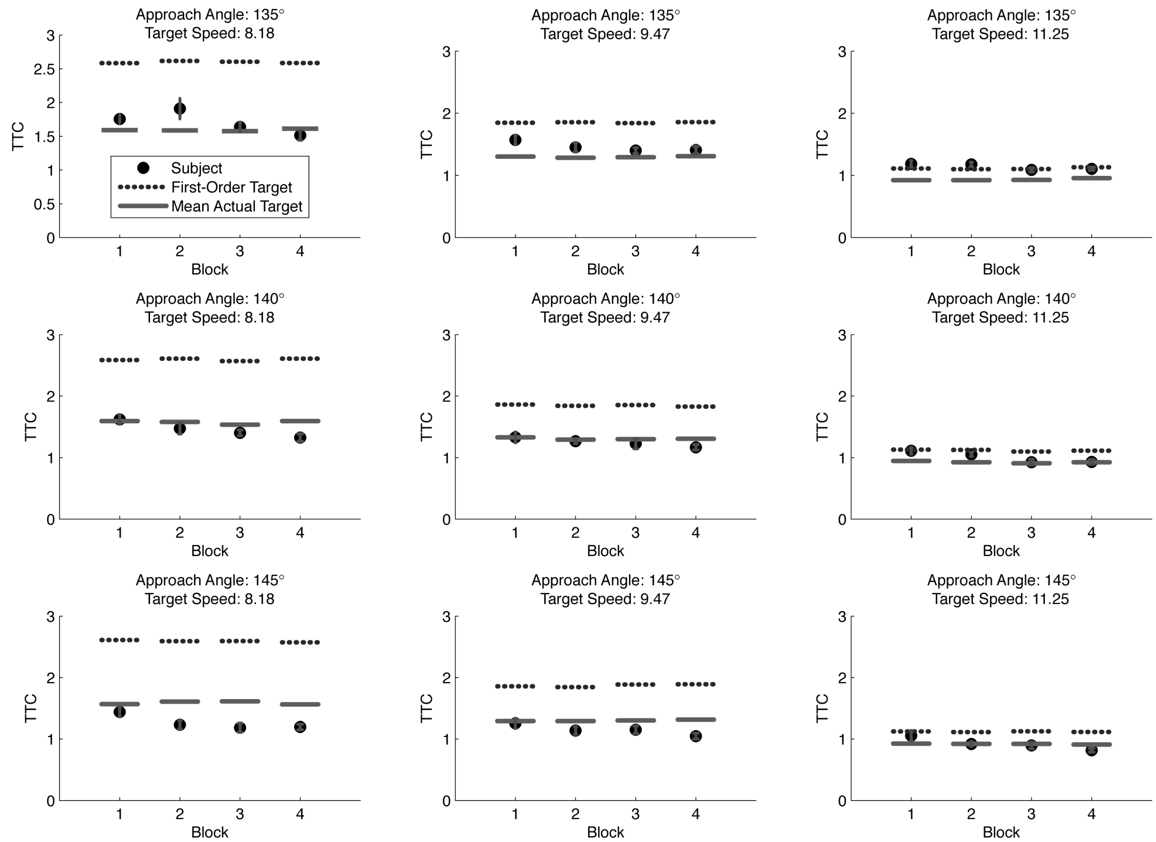

Figure 5: A comparison of subject TTC, first order target TTC, and mean actual target TTC at the onset of the target's change in speed.

Differences in subject TTC and measures of target TTC appear to have varied with the target's approach angle and speed: subject TTC was consistently greater than the first-order target TTC when the target was approaching from a less head-on angle at a high speed (the top-right of Figure 5), and lower than mean actual TTC values when a more slowly moving target approached from more head-on trajectory (the lower-left of Figure 5). A three-way repeated measures ANOVA confirmed main effects of initial target speed $F(2,20)=112.85$, $p \leq .001$, approach angle $F(1.33,13.1)=95.263$, $p \leq .001$, and block $F(3,30)=11.30$, $p \leq .001$. In addition, there was an interaction of initial target speed and angle on the subject's TTC $F(1.55,15.54)=4.17$, $p=.044$.

The main effect of initial speed simply reflects the effect that the target's initial speed has upon the overall time it takes for the target to reach the interception point. Simply put, the subject must increase his or her speed in order to catch faster moving targets. Subjects also had a lower TTC at onset when the target's initial approach angle was larger and thus closer to a head-on approach. This may be due to the fact that greater approach angles were accompanied by a smaller initial visual angle between the target and the subjects' heading.

The interaction between target speed and approach angle is most evident when the target approached from the head-on trajectory (145˚) at the slowest speed (8.18 m/s). These conditions elicited the greatest discrepancy between subject TTC and mean actual target TTC. They are also the conditions in which the target spends the greatest amount of time within +/- 0.35 meters of the subject's path of motion (the minimum distance necessary for a successful interception). The implication is that the large temporal window for successful interception allowed subjects the opportunity the flexibility to compensate for poor anticipation.

2.3.4 Did subjects use a task-specific heuristic?

One might wonder if subjects adopted a simple task-specific heuristic that worked within the range of conditions experienced in this experiment, but would not work when conditions vary across a wider range. Of course, there are an infinite number of possible heuristics. In this section, two such heuristics will be considered and ruled out.

One possibility is that subjects developed a stereotyped pattern of velocity adjustments that could be applied independently of the initial conditions to get within the ballpark. However, my analysis of the mean subject TTC at onset indicates that behavior was influenced by the initial condition (Figure 5).

The second possible heuristic that was considered was that subjects tried to maintain a constant non-zero rate of change in bearing angle. To investigate this possibility, a 3-way ANOVA was performed to test the effects of approach angle, initial target speed, and block on the rate of change in bearing angle at onset (Figure 4). The rate of change in bearing angle increased with both the target's approach angle $F(2,20)=66.48$, $p \leq .001$, initial target speed $F(1.33,13.30)=33.42$, $p \leq .001$, and block $F(3,30)=9.47$, $p \leq .001$. There was also an interaction between angle and initial target speed $F(2.05,20.50)=7.96$, $p \leq .003$, and a marginally significant interaction between initial target speed and block $F(6,60)=2.25$, $p \leq .05$. The inconsistency of the rate of change in bearing angle across initial conditions rules out the possibility that subject simply tried to maintain a constant non-zero rate of change in bearing angle at onset.

2.3.5 Summary

The results of Experiment 1 suggest that subjects do not use the constant bearing angle strategy to intercept targets that change speeds. Instead, values of subject TTC at onset more closely match predictions that assume accurate anticipation of the most likely change in target speed given both previous experience and the trial's initial conditions.

3. Experiment 2

Experiment 1 demonstrated that subjects were able to develop accurate expectations of probable changes in target speed. Experiment 2 tests whether these findings will generalize to a new situation, in which the target approaches along a curvilinear path with either concave curvature that bends away from the subject, or convex curvature that bends towards the subject (Figure 6).

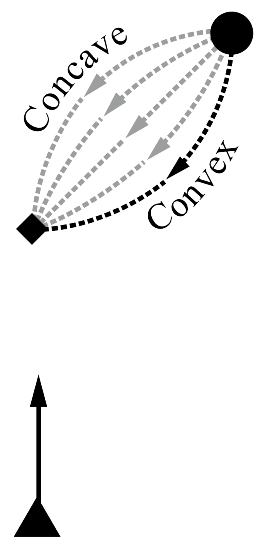

Figure 6. An overhead view of the task in Experiment 2. The pursuer is marked by a triangle, and the target by a circle.

Experiment 2 is similar to the Experiment 1 in that use of a pure constant bearing angle strategy will often result in a failed interception. This is especially true on trials with large convex curvature: if a subject maintains the bearing angle early in the trial when the target's heading is roughly parallel to the subject's path of motion, then the subject will be forced to continually increase his or her velocity as the target's heading moves in the direction that is roughly perpendicular to the subject's path of motion (The dark dotted line in Figure 6). If the subject reaches maximum speed before interception, he or she will be unable to maintain a constant bearing angle, and unable to intercept the target.

To avoid this situation subjects might make adjustments early in the trial in anticipation of the expected change in target heading. Bastin et al. (2006b) showed that actors cannot predict the eventual time and location of the future interception point for curvilinear targets. However, even if actors do not rely on such long-term predictions, they may still be able to gain an advantage by anticipating the change in target direction a brief period into the future. The problem then becomes one of learning the correct pedal adjustment at time t that will produce a constant bearing angle at time $t+\Delta t$. Because the bearing angle is a function of both the target's and the subject's behavior, solving this problem requires that subjects take into account the expected target dynamics. These expectations may be encoded in terms of a learned mapping from a desired future state with a constant bearing angle at time $t+\Delta t$ to the velocity adjustment at time t that is necessary to bring about this desired future state.

Interestingly, this simple characterization of anticipatory behavior might be used to of explain a spectrum of possible human behavior by simply varying the value of Δt: if Δt is close to zero, the modeled velocity adjustments will resemble those of a subject using a pure constant bearing angle strategy. Greater values of Δt will produce behavior that suggests perfect anticipation of the future time and location of the target's passage over the subject's path of motion. By comparing subject velocity adjustments with those of ideal pursuers with varying values of Δt, I am able to estimate the temporal distance across which subjects are able to anticipate future target dynamics.

3.1 Methods

3.1.1 Participants

Twelve undergraduates from the Rensselaer Polytechnic Institute participated in the experiment. Each had normal or corrected-to-normal vision.

3.1.2 Displays and Apparatus

The stimuli were identical to those of Experiment 1, with the following exceptions. The initial position of the target was 40 m from the interception point and 135° or 145˚ from the subject's path of motion. The target moved at an initial tangential speed of 10 m/s or 8.89 m/s, corresponding to initial time-to-contact values 4s and 4.5s, along one of five trajectories, four of which were curvilinear, and one of which was rectilinear. The radii of the curvilinear paths were 35m or 60m, and the direction of a path was either concave in that it bent away from the pursuer, or convex in that it bent toward the pursuer. The 2 (initial target angles) x 2 (initial target speeds) x 5 target path curvature x 5 (repetitions) x 3 (block) design produced a total of 300 trials per subject during the experimental session.

As in Experiment 1, subjects had lagged first-order control of their speed defined by Equation 1. However, the lag coefficient was adjusted to .03 to accommodate the different conditions in Experiment 2. The change in lag coefficient had the effect of allowing the actual speed to more closely follow the speed defined by the position of the pedal. The minimum speed was 0 m/s and the maximum was 15 m/s.

3.2 The Model

This section describes the model, and how it was used to generate predictions for different values of Δt between zero and the actual TTC of the target. To anticipate, the model selected (at each time step) the speed adjustment that nulled the change in bearing angle at some future time $t+\Delta t$, taking into account the dynamics of the controlled system and the behavior of the target up until $t+\Delta t$.

3.2.1 Initial conditions, target behavior, and controller dynamics

The initial conditions and target behavior were identical to those used in the actual experiment. In order to make the model as realistic as possible, it was also necessary to incorporate into the model the various sources of controller lag that subjects experienced in the actual experiment. Due to the inertia of the subject's foot and the foot pedal system, all pedal adjustments in the actual experiment were smooth and continuous. In addition, recall that there was a first-order lag between the position of the foot pedal and the simulated speed. These two sources of lag were combined in the model by adding a second-order lag between the intended speed selected by the model and the current speed. More specifically, the agent's actual speed was treated as an over-damped harmonic oscillator about the intended speed. Calculations were made using the Matlab function ODE45 that, at each time-step t, solved the equation:

$$\ddot{v} = -\beta \times \dot{v} - \omega_0^2 \times (v - v^*) \tag{2}$$

where v is the current speed, $\dot{v}$ is acceleration , $\ddot{v}$ is jerk, and v^* is the intended speed. This introduced two additional free parameters: the damping term β, and the (undamped) natural harmonic frequency ω_0^2. Speed was recovered by taking the double integral of jerk.

3.2.2 Assumptions

The intended speed selected by the model at each time step was based on perfect knowledge of both the controller dynamics and the target's behavior from t to $t+\Delta t$. Because the controller dynamics were fixed, and subjects practiced the task before the experiment began, it is reasonable to assume that they were familiar with the controller dynamics. Of course, one cannot assume that subjects actually knew the future behavior of the target on each trial. Nonetheless, it might be possible to learn a control strategy that allows one to take advantage of regularities in the target's behavior, without actually having explicit knowledge of such behavior. [This is analogous to the way in which outfielders learn a control strategy that allows them to move into position to catch a fly ball without having explicit knowledge of the dynamics of projectiles (e.g., McLeod et al. 2006)]. My aim here is not to address the issue of how such a control strategy could be learned, but rather to determine if such a model could account for human behavior. If it can, then a logical next step would be to explain how the control strategy is learned.

3.2.3 Updating speed

The model updated intended speed at 60 Hz, equal to the frame rate of the display used in Experiment 2. To reflect the fact that the human subjects needed time to react after the onset of the display, no speed adjustments were made for the first 330 ms of each trial. This duration corresponds to the average trial time (calculated across all trials and all subjects) at which speed adjustments were initiated.

At each time-step after 330 ms, the intended speed that would null the change in bearing angle at time $t+\Delta t$ was found via brute-force search of each possible speed from 0 to the maximum speed of 15 m/s, with a search resolution of .25 m/s. For each possible intended speed, the change in position and speed from t to $t+\Delta t$ was calculated using the universal oscillator equation (see above). The position and speed at time $t+\Delta t$ was then used together with the position and speed of the target at time $t+\Delta t$ to calculate the rate of change in bearing angle, which was then stored in an array. Once all possible intended speeds had been tested, the intended speed that produced the minimum change in bearing angle at time $t+\Delta t$ was selected for that time-step.

3.2.4 The Process of Fitting

The model was used to find the set of parameters (Δt, β, and ω_0) that best fit the human data. The three parameters were always fixed within each simulated trial. Because some trajectories may be more predictable than others, the parameters were allowed to vary across target radius and direction, but were fixed across initial target speed and approach angle.

The model was fit to the mean speed profile from the human data. The speed profiles from each trial in the actual experiment were averaged across repetitions within a condition, and then across subjects. This resulted in 48 mean speed profiles (4 radius/direction pairs × 2 initial target speeds × 2 target approach angles × 3 blocks)[2]. The RMSE between the speed profiles produced by the model and by human subjects was then calculated. The parameters β, and ω_0 were fixed at the values that produced the least total RMSE across the four radius/direction pairs, while the parameter Δt was allowed to vary.

3.2.5 The Search Space

The process tested each value of ω_0 between 2.5 and 4.5 in increments of .25. The parameter β was defined as a scalar multiple of ω_0, where a scalar of 2 produces a critically damped oscillator, values greater than 2 produce an over-damped oscillator, and values less than 2 produce an under-damped oscillator. The scalars used to define β ranged from 2 to 4.5 in increments of .25. The range of Δt values explored extended from .25 to 3.5 in increments of .25. The lower values of .03 and .5 were also included in the fitting process.

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[2] For each combination of radius/direction, initial target speed, and target approach angle, the model was then used to produce one simulated speed profile for each possible combination of Δt, β, and ω_0.

3.3 Results and Discussion

3.3.1 Task Performance:

The average hit rate for all subjects improved from 38.8% in block 1, to 51.5% in block 2, to 56.3% in block 3 $F(2,22)=27.051$, $p \leq .001$. Repeated measures contrasts across blocks indicate that performance on block 2 was significantly different than performance on block 1 $F(1,11)=38.183$, $p \leq .001$, and that performance on block 3 was significantly different than performance on block 2 $F(1,11)=21.111$, $p \leq .002$. Performance also differed by radius/direction pair that defined the targets trajectory $F(2.08,22.95)=33.403$, $p \leq .001$. Visual inspection suggests that performance was worst on largely convex trials, better on less convex trials, and best for rectilinear and concave curvatures (Figure 7). A significant interaction was found between block and curvature $F(8,88)=3.114$, $p \leq .005$, possibly because improvement across blocks appears to have been greatest on conditions in which initial performance was poorest. This is most probably due to a ceiling effect on performance during concave trials.

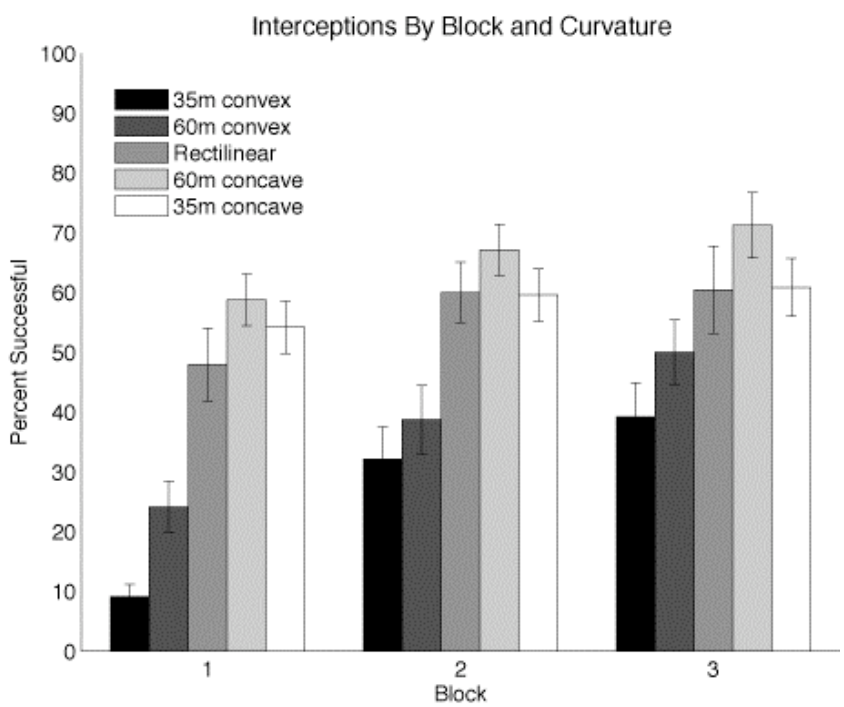

Figure 7: Percentage of successful interceptions by block and curvature.

3.3.2 Subject Velocity Profiles

A five-way ANOVA was used to investigate variations of subject velocity in response to changes in radius/direction pair, target approach angle, initial target speed, block, and time. Time was incorporated by sampling subject velocity at 1 second intervals from .5 seconds until 3.5 seconds into the trial.

If subjects used a pure prediction strategy, then I should find similar subject behavior when target trajectories share a mean value of initial target speed, however, the evolution of subject velocity over time differed by radius/direction pair $F(12,132)=90.738$, $p\leq.001$ (Figure 8). On convex trials, if subjects were using a pure CBA strategy, then subject speed would have monotonically increased at an increasing rate as the target's heading shifted away from a direction that was roughly parallel to the subject's path of motion and toward a direction that was roughly perpendicular to the subject's path of motion. Consistent with this prediction, the mean subject velocity increased monotonically, however, the majority of acceleration takes place early in the trial rather than later, and velocity changes little towards the end of the trial when the change in bearing angle is greatest. This suggests that subjects have learned to anticipate the predictable evolution of the target's trajectory, and that the model will best fit the velocity profiles with intermediate to higher values of Δt.

On concave trials, subjects accelerate early in the trial and decelerate later in the trial. If the subjects were using a pure CBA strategy then speed would have increased early in the trial when the target's heading was roughly perpendicular to the subject's path of motion. Subsequently, subject velocity would decrease as the target's motion shifted toward a direction that was roughly parallel to the subject's path of motion. Qualitatively, the observed velocity profiles match this prediction, suggesting that the model will best fit the velocity profiles with intermediate to lower values of Δt.

Subject velocity profiles within each radius/direction pair appear to be grouped according to initial target speed, and to be unaffected by approach angle. Consistent with this observation, an interaction of sample and initial target speed was found $F(3,33)=107.841$, $p\leq.001$, whereas none was found between sample and approach angle $F(3,33)=1.608$, $p=.206$. The significant sample x initial target speed interaction simply captures the fact that subjects must travel faster to intercept faster targets. The nonsignificant sample x approach angle interaction is also adaptive, as the target reaches the interception point at the same time regardless of approach angle.

To summarize, velocity profiles differed by radius/direction pair, as well as the initial target speed, but not by approach angle. On convex trials, qualitative evidence suggests the use of anticipatory strategies that will be most closely approximated with intermediate to high values of Δt. On the other hand, concave trials conform to predictions of a CBA strategy, and thus I should expect to see that the model will best fit the data with lower values of Δt. Though performance varied across blocks ($F(2.958,32.535)=8.981$, $p=.001$), the qualitative properties of these interactions appear to be consistent.

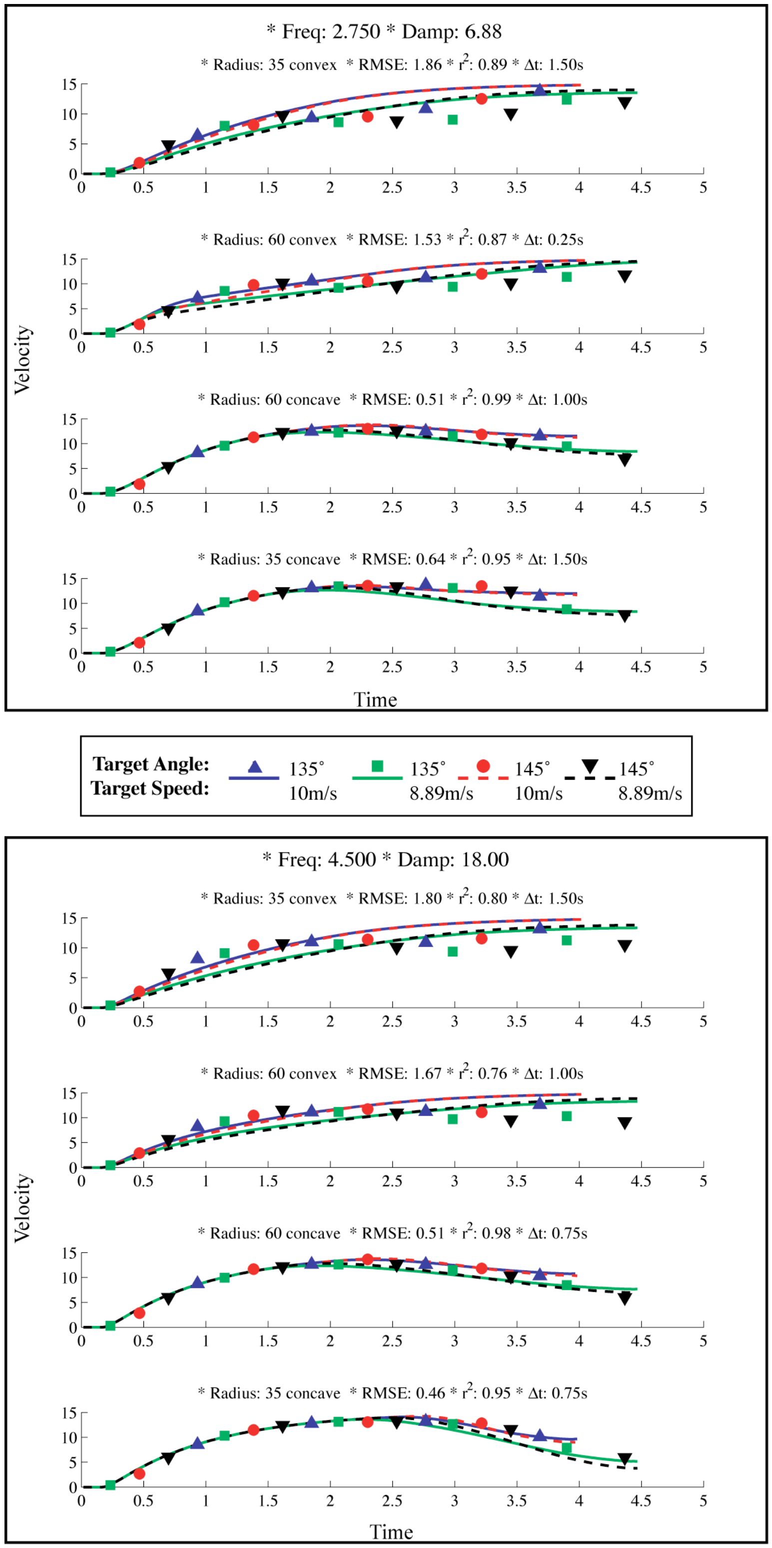

Figure 8. Mean subject velocity (shapes) and simulated velocity (lines) for block 1 (top) and block 3 (bottom).

3.3.3 Modeling Performance

The model was able to capture the grouping of velocities according to the initial target speed within each radius/direction pair, with higher simulated velocities accompanying higher values of initial target speed (Figure 8). Like the subject data, the simulated velocity profiles were unaffected by the initial approach angle.

The model was also able to capture the early increase in simulated velocity seen on concave trials, as well as the subsequent and gradual decrease. The resulting RMSE values were low relative to those produced on convex trials, where error arose from the model's inability to capture the plateau seen in subject velocity. Instead, the model's velocity increased at a relatively steady rate throughout the trial, producing a simulated velocity that was slightly lower than subject velocity earlier in the trial, and greater than the subject velocity later in the trial.

The consistency of Δt across blocks suggests that the improvement in subject performance is not due to anticipation further into the future. An alternative explanation is that subjects are instead developing more accurate expectations of changes in the target's trajectory from time t to time $t+\Delta t$.

Unlike Δt, the best fitting values of frequency and damping differed greatly between block 1 and block 3. Whereas in block 1 the best fitting frequency was the second lowest of the range of values that was searched, in block 3 it increased to the greatest of searched values. Damping, which was the product of frequency and a scalar multiple (see section 3.2.5), followed a similar trend; damping was the smallest possible value on block 1, and the largest possible value in block 3.

4. General Discussion

The purpose of this study was to examine human control strategies for the interception of moving targets that change velocity. Experiment 1 tested for the ability to accurately anticipate probable changes in the target's speed. Shortly after the start of each trial, the target accelerated to a new speed that was randomly selected from a Gaussian distribution. The question was whether subjects could learn how to modulate their speed during the first part of the trial in anticipation of the change in target speed that was most likely based on past experience. Subject behavior matched predictions that take into account the most probable change in target speed given past experience and the initial conditions of that trial. The implication is that, given the insufficiency of a CBA strategy to deal with changes in target speeds, subjects adopted a strategy that exploited statistical regularities in the target's behavior to anticipate the most probable change in target speed.

Whereas, in Experiment 1, the change in the target's trajectory occurred over a short duration (.5s), targets in Experiment 2 approached along curvilinear paths, causing a continuous change in trajectory throughout the trial. Though these simple and continuous changes in target trajectory would seem ideal for a predictive model of interception, Bastin, Craig, and Montagne (2006b) found that subject behavior was more consistent with a CBA strategy of interception than a pure prediction of the future time and location of the target's passage over the interception point. I extend this research by investigating intermediate strategies, by which the subject's behavior is reliant upon a short-term prediction of the future state of the bearing angle.

This hypothesis was implemented in a model that, at each time t, makes an adjustment that will null the change in bearing angle at the future time $t+\Delta t$. For values of Δt near zero, behavior will be consistent with a CBA model of interception. Values of Δt that are close to the target's time-to-contact with the interception point will produce behavior that more closely resembles a strategy of pure prediction.

The model produced simulated velocity profiles that appear similar to subject profiles, especially on trials on which the target approaches along a concave path. The model was also able to capture differences in subject velocity that accompany changes in the magnitude and direction of the target's curvature, as well as the observed effects of initial target speed, and the non-effect of approach angle.

The model did not do a good job at capturing relevant aspects of learning. Subject performance consistently improved with experience, most noticeably on convex trials. However, the simulated velocity most closely approximated subject velocity with values of Δt that were roughly constant across blocks, suggesting that learning was unrelated to the value of Δt, corresponding to the duration of anticipation. That the best fitting values of frequency and damping lie at the limits of the search space suggests that the search space may not have been wide enough, or may not have been searched finely enough to capture the best fitting values of Δt. In either case, additional modeling is necessary.

4.1 From Feedback to Prediction

My model is consistent with certain aspects of *information based control* (Warren 1998), which suggests that action is mediated by a control law operating upon visual information available within the optic array. Consistent with Warren's definition, my control law is task-specific, and operates on the basis of task-specific control information (e.g. the rate of change in bearing angle). However, the model differs from many other information-based models in that movements are made to bring about a desired optical consequence (e.g., a constant bearing angle) at some point in the near future. This difference, though subtle, necessitates at least two forms of learning that are not typically considered in theories of information based control: the actor must learn a mapping from the current state to a tenable desired future state, and the actor must learn how to choose an appropriate action that will bring this desired state about. Similar inverse problems where a desired outcome precipitates the causal action are commonplace in motor control literature resulting in a variety of frameworks with which one might model the learning of solutions (Jordan and Wolpert 1999).

My framework also brings new insight to the dichotomized models of prospective control, that link action to temporally proximal events as they unfold, and predictive control, in which a control plan is chosen on the basis of a temporally distant desired outcome (Montagne 2005). My model straddles this dichotomy by linking action in a prospective manner to a temporally distant desired outcome that changes as new information is received. This new characterization adds new explanatory power to theories of information-based control. For example, the theory suggests a new robustness to interrupted visual feedback, in which case the coupling of action to a mapping of the expected future state would allow for a short duration of continued accurate behavior.

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6. Appendix 1

One-Sample t-Tests
(Subject TTC - Target TTC) Vs. Test Value of 0
DOF = 10

Block #	Velocity (m/s)	Angle (Degrees)	t	Significance (2-tailed)	Mean Difference	95% Confidence Interval of the Difference Lower	Upper
1	8.18	135	1.40	0.193	0.07	-0.04	0.19
		140	1.57	0.147	0.08	-0.03	0.18
		145	-0.34	0.741	-0.01	-0.11	0.08
	9.47	135	-0.81	0.440	-0.03	-0.10	0.05
		140	-3.87	≤.001	-0.28	-0.44	-0.12
		145	-5.96	≤.001	-0.41	-0.56	-0.25
	11.25	135	-11.24	≤.001	-0.44	-0.53	-0.35
		140	-7.40	≤.001	-0.45	-0.59	-0.31
		145	-11.02	≤.001	-0.83	-0.99	-0.66
2	8.18	135	-4.54	≤.001	-0.71	-1.05	-0.36
		140	-11.27	≤.001	-0.97	-1.16	-0.77
		145	-12.14	≤.001	-1.07	-1.27	-0.87
	9.47	135	-0.37	0.718	-0.02	-0.13	0.10
		140	-2.96	0.014	-0.07	-0.13	-0.02
		145	-3.85	≤.001	-0.17	-0.27	-0.07
	11.25	135	-5.19	≤.001	-0.18	-0.26	-0.10
		140	-5.68	≤.001	-0.53	-0.74	-0.32
		145	-11.61	≤.001	-0.58	-0.69	-0.47
3	8.18	135	-7.65	≤.001	-0.63	-0.81	-0.44
		140	-14.25	≤.001	-0.66	-0.77	-0.56
		145	-12.31	≤.001	-0.96	-1.14	-0.79
	9.47	135	-12.93	≤.001	-1.14	-1.33	-0.94
		140	-20.69	≤.001	-1.17	-1.29	-1.04
		145	-20.00	≤.001	-1.28	-1.43	-1.14
	11.25	135	-0.85	0.416	-0.07	-0.25	0.11
		140	-3.45	0.006	-0.19	-0.32	-0.07
		145	-5.29	≤.001	-0.23	-0.33	-0.13
4	8.18	135	-8.00	≤.001	-0.30	-0.38	-0.22
		140	-7.03	≤.001	-0.60	-0.79	-0.41
		145	-10.88	≤.001	-0.71	-0.85	-0.56
	9.47	135	-12.42	≤.001	-0.74	-0.87	-0.61
		140	-16.84	≤.001	-0.84	-0.96	-0.73
		145	-14.67	≤.001	-1.17	-1.35	-0.99
	11.25	135	-18.73	≤.001	-1.36	-1.52	-1.20
		140	-20.34	≤.001	-1.41	-1.57	-1.26
		145	-27.16	≤.001	-1.38	-1.49	-1.26

7. Appendix 2

One-Sample t-Tests
(Subject TTC - Mean Actual TTC) Vs. Test Value of 0
DOF = 10

Block #	Velocity (m/s)	Angle (Degrees)	t	Significance (2-tailed)	Mean Difference	95% Confidence Interval of the Difference	
						Lower	Upper
1	8.18	135	4.71	≤.001	0.26	0.14	0.39
		140	5.73	≤.001	0.25	0.16	0.35
		145	4.25	0.002	0.16	0.08	0.25
	9.47	135	4.28	0.002	0.15	0.07	0.23
		140	4.27	0.002	0.27	0.13	0.41
		145	2.32	0.043	0.17	0.01	0.33
	11.25	135	2.55	0.029	0.11	0.01	0.20
		140	1.63	0.134	0.10	-0.04	0.23
		145	2.07	0.065	0.17	-0.01	0.34
2	8.18	135	2.13	0.059	0.32	-0.02	0.66
		140	0.84	0.421	0.06	-0.10	0.23
		145	-1.07	0.312	-0.10	-0.30	0.11
	9.47	135	3.63	0.005	0.17	0.06	0.27
		140	4.33	0.002	0.13	0.06	0.19
		145	0.32	0.755	0.02	-0.10	0.13
	11.25	135	0.06	0.951	0.00	-0.09	0.10
		140	0.00	0.998	0.00	-0.21	0.22
		145	-0.50	0.626	-0.02	-0.13	0.08
3	8.18	135	-0.86	0.413	-0.07	-0.26	0.12
		140	-2.53	0.030	-0.14	-0.26	-0.02
		145	0.35	0.737	0.03	-0.15	0.20
	9.47	135	-1.17	0.270	-0.11	-0.31	0.10
		140	-2.47	0.033	-0.13	-0.25	-0.01
		145	-4.21	0.002	-0.27	-0.41	-0.13
	11.25	135	1.61	0.139	0.13	-0.05	0.31
		140	-0.06	0.955	0.00	-0.13	0.12
		145	-0.56	0.587	-0.03	-0.12	0.07
4	8.18	135	-2.78	0.019	-0.09	-0.17	-0.02
		140	-0.46	0.653	-0.04	-0.22	0.14
		145	-2.18	0.054	-0.15	-0.31	0.00
	9.47	135	-2.61	0.026	-0.15	-0.28	-0.02
		140	-5.53	≤.001	-0.27	-0.38	-0.16
		145	-1.47	0.172	-0.13	-0.32	0.06
	11.25	135	-4.67	≤.001	-0.38	-0.56	-0.20
		140	-6.21	≤.001	-0.43	-0.59	-0.28
		145	-7.80	≤.001	-0.37	-0.47	-0.26