Exp Brain Res (2009) 195:345–360
DOI 10.1007/s00221-009-1794-5

RESEARCH ARTICLE

Intercepting moving targets: a little foresight helps a lot

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Received: 14 July 2008 / Accepted: 31 March 2009 / Published online: 26 April 2009

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 anticipatory strategy of moving so as to produce a CBA a short duration into the future. Subjects controlled their speed of self-motion along a linear path through a simulated environment to intercept a moving target. When targets changed speed midway through the trial in Experiment 1, subjects abandoned an ineffective CBA strategy in favor of a strategy of anticipating the most likely change in target speed. In Experiment 2, targets followed paths of varying curvature. Behavior was inconsistent with both the CBA and the purely predictive strategy. To investigate the intermediate anticipatory strategy, 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 0.5 and 3.5 s, suggesting that actors adopt an anticipatory strategy to keep the bearing angle constant a short time into the future.

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Keywords Interception · Locomotion · Visual control · Anticipation

Introduction

Running to intercept a target moving across the ground plane is one of the basic locomotor tasks performed by creatures ranging from predators in the wild to humans on the playing field. The study of locomotor interception has provided a window onto the nature of the information–movement coupling that characterizes many forms of visually guided behavior. However, most of the efforts (both theoretical and empirical) to understand locomotor interception have been directed at the interception of constant velocity targets. In only a small number of studies is it acknowledged that moving targets change speeds and directions, oftentimes in ways that cannot be perfectly predicted. In this study, we begin by considering the usefulness of previous models designed for constant velocity targets within a somewhat more realistic context that involves targets that change speed or direction. We then present two experiments designed to investigate human behavior in this situation. In Experiment 1, subjects were tested for the ability to accurately anticipate probable changes in a target's speed. 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 to 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 behavior of the ideal provided an indication of subjects' ability to act so as to bring about a desired future state that is dependent 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, the defenseman's task of intercepting the ball carrier is complicated by unpredictable changes in the speed and direction of the ball carrier as he evades pursuit. The experienced defenseman orients his approach in anticipation of these changes and in such a way that limits the ball carrier's chances of evasion. In other words, an effective control strategy accounts not just for current target behavior, but also for the possible changes in behavior.

The constant bearing angle model

The most widely accepted model of locomotor interception is based on a strategy that has been used for centuries by sailors to avoid collisions with nearby vessels (Le Brun 2002). Known amongst scientists as the CBA model of interception, the strategy proposes that by maintaining a CBA the observer is guaranteed to intercept the moving target. The bearing angle (Ψ) is the direction of the target with respect to an exocentric reference line (see Fig. 1).[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. As would be expected based on the CBA hypothesis, subjects perceive an impending collision when their self-motion is accompanied by the movement of a target whose bearing angle remains constant (Cutting et al. 1995). In addition, the active interception strategies of both humans and of several non-human animals including dragonflies (Olberg et al. 2000) and teleost fish (Lanchester and Mark 1975) conform to the predictions of the CBA model. 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 two studies to test the CBA strategy in humans were reported by Lenoir et al. (1999a, 1999b). Subjects were instructed to hit a target moving along a track by controlling their approach speed on a tricycle with heading

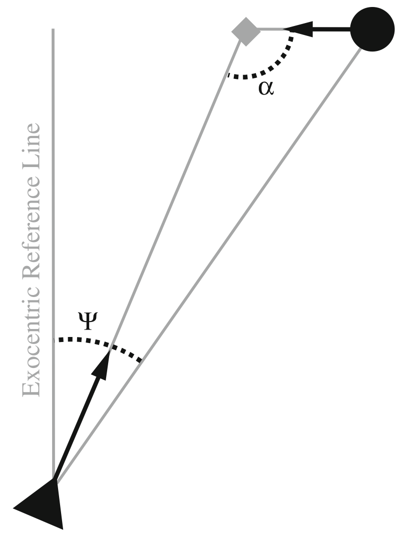


Fig. 1 An overhead view of an exemplary interception situation. The pursuer (*triangle*) and target (*circle*) approach the invisible interception point (*diamond*). Ψ denotes the exocentric direction of the target (bearing angle) and α denotes the target's approach angle

fixed. Although results were consistent with the CBA model, the task was somewhat oversimplified due to technical limitations. The target's movement was restricted to one approach angle, and the target moved at one of only two possible speeds. Each speed 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, limiting the analysis to the final seconds of approach. Thus, although the data were suggestive of a CBA strategy, the findings were far from conclusive due to methodological limitations.

In a subsequent study (Lenoir et al. 2002), more conclusive findings were provided by showing that behavior was still consistent with the CBA model even when there was more variety in initial conditions and the task and environment were more natural. Chardenon et al. (2005) found that subjects walking on a treadmill adjust locomotor speed in accordance with the predictions of the CBA model, making more pronounced velocity adjustments when the target approaches from a greater (i.e., more orthogonal) angle. Whereas locomotor heading was fixed in the aforementioned studies, subjects in Fajen and Warren (2004) intercepted moving targets while walking in a large area virtual environment that also permitted changes in walking direction. They found that subjects turn while walking until they lead the target by a bearing angle that can be maintained until interception.

Compelling support for the CBA strategy was provided by Bastin et al. (2006) using targets that approached along

[1] Fajen and Warren (2007) presented simulations to show that the bearing angle whose change must be nulled is defined in an exocentric reference frame. When simulated agents keep the target at a constant egocentric (rather than exocentric) direction, the resulting trajectory spirals behind the moving target for some initial conditions. By comparison, human subjects follow a straight path ahead of the target (Fajen and Warren 2004).

curvilinear paths. The experiment was set up in such a way that, on a subset of trials, subjects could successfully intercept the target without changing speed. No speed adjustments were necessary on such 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. Although 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.

To summarize, numerous previous studies on locomotor interception suggest that actors adjust locomotor speed and/or direction to keep the target at a CBA. Additional past research on this problem was aimed at uncovering the informational basis for perception of the change in bearing angle, and specifically, the contributions of visual, proprioceptive, vestibular, and podokinetic information (Fajen and Warren 2004; Bastin and Montagne 2005; Chardenon et al. 2005; Fajen and Warren 2007).

Interception strategies in the presence of variability

Unlike the experimental conditions in which the CBA model has been tested, real world conditions are subject to sources of variability that may complicate behavior. In an interception task variability may arise from unpredictable changes in target velocity. Consider the (admittedly unrealistic and predictable) situation in which the target moves along the same trajectory at the same initial speed as on every other trial until a certain moment at which it accelerates to some new speed, which is also the same on every 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 model 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) immediately following the change in target speed.

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? Because both target heading and subject heading are fixed, the point of interception is defined in advance. We 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 target speed does not change. Before the pursuer has enough experience to realize that the target always accelerates, it is expected that she will adjust speed in such a way that 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 even before the target accelerates so that her TTC with the interception point equals the target's actual TTC with the interception point. Once the pursuer's TTC is equal to the target's actual TTC, the pursuer can simply maintain speed to intercept the target. Note that this 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, our objective here is simply to explain how the data will be analyzed to test the hypothesis that actors 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.

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, we 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.

Methods

Participants

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

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 × 1024 onto a 1.8 × 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 1 m 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 0.35 m approached the observer's path of motion from the right side (see Fig. 2).

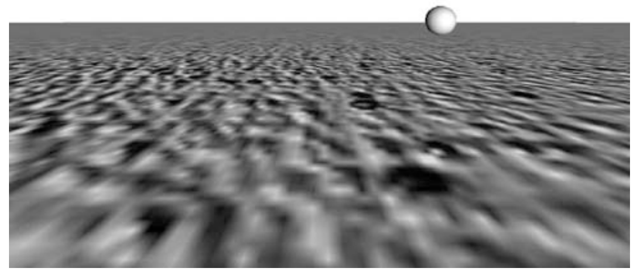


Fig. 2 A sample frame of the experimental stimulus

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 Fig. 1). The target traveled along a fixed path at one of three initial speeds 11.25, 9.47, 8.18 m/s, which correspond to initial first-order time-to-contact values of 4, 4.75, 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 25 and 30 m. Subjects' velocity had a lagged first-order relationship with the pedal position, defined by the equation:

$$\dot{V} = K * \left(V_p - V_s\right) \quad (1)$$

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 0.017 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 to 14 m/s. To successfully intercept the target, the subject had to pass within a distance of 0.35 m from the center of the target.

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 which each possible combination of initial approach angle and initial target speed was presented once, producing a total of nine practice trials. During the experimental session, each combination was presented ten times within each of four blocks. The

3 (initial approach angles) × 3 (initial target speeds) × 10 (repetitions) × 4 (block) design produced a total of 360 trials during the experimental session.

Results and discussion

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 (Fig. 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° 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 $X^2(6, N = 3{,}960) = 57.00$, $p \leq 0.001$.

Did subjects use a constant bearing angle strategy?

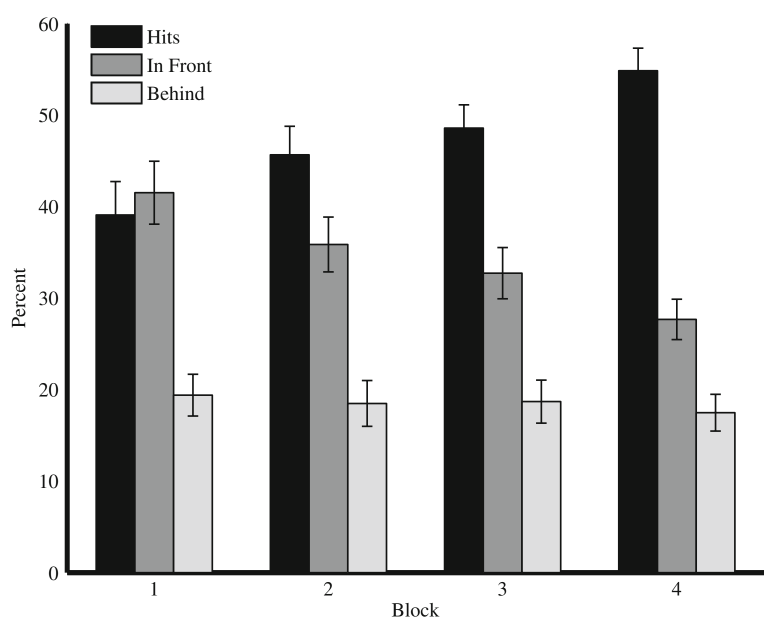
The remaining analyses were based on measurements taken on the frame immediately before the onset of the target's acceleration from its initial speed to its final speed (hereafter referred to simply as the "onset"). The reason for taking measurements at onset is twofold: (1) subjects do not yet have visual information about the magnitude of the impending change in target speed, and (2) if subjects are going to modulate their approach speed in anticipation of the target's likely change in speed, they will have had sufficient time to do so in the 2.5–3.25 s before the target changes speed.

If subjects used a CBA strategy, then the instantaneous change in bearing angle at onset should be close to zero. *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 $p \leq 0.001$ for each individual *t* test (Fig. 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.

Furthermore, if subjects were using a CBA strategy, then subjects' TTC should match the target's first-order TTC at onset. This was clearly not the case (Fig. 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 Bonferroni tests for each of the 36 conditions (3 initial speeds × 3 approach angles × 4 blocks). Of the 36 tests used to test for a statistically significant difference between the subject's TTC and the target's first-order TTC, 28 show a significant difference from zero.

To summarize, there was no evidence that subjects were trying to maintain a constant bearing angle during the first

Fig. 3 Percentage of trials in which the target was successfully hit, passed in front of the observer, or passed behind the observer in Experiment 1



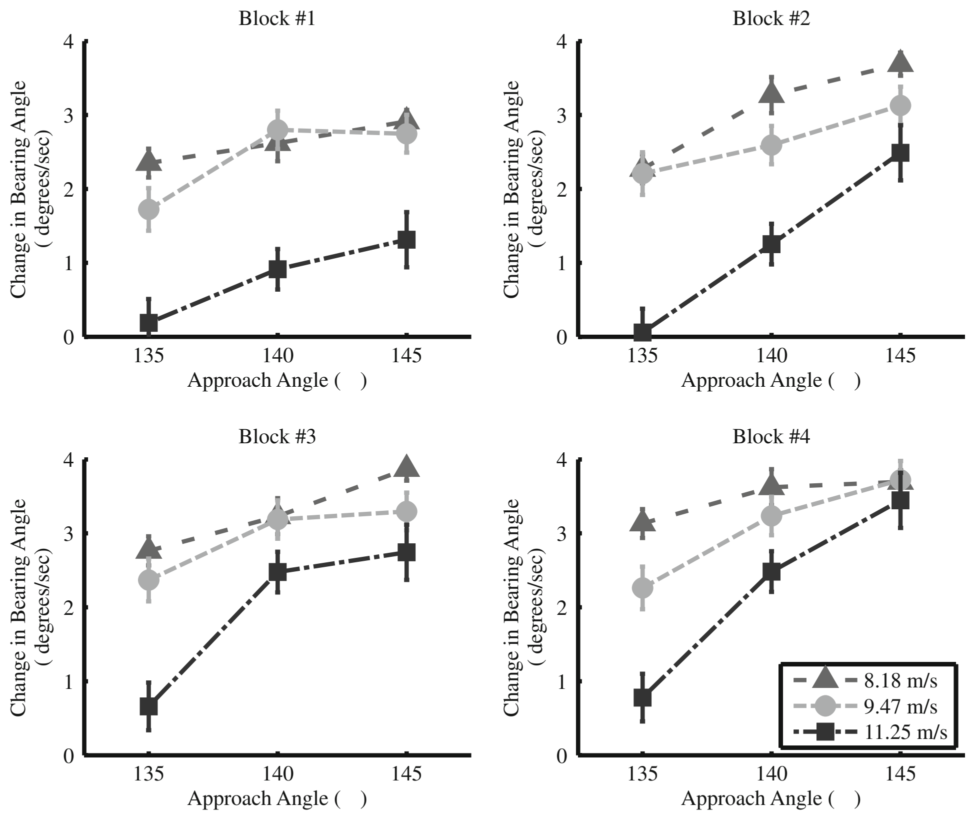


Fig. 4 Change in bearing angle at onset by initial target speed, approach angle, and block

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.

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 Fig. 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 significantly different from first-order TTC (28 of 36 Bonferroni tests), and mean actual TTC (18 of 36 t tests).[2]

Differences in subject TTC and measures of target TTC appear to have varied with the target's approach angle and speed: subject TTC was sometimes greater than the first-order TTC when the target was approaching from a less head-on angle at a high speed (the top-right of Fig. 5), and lower than mean actual TTC values when a more slowly moving target approached from more head-on trajectory (the lower-left of Fig. 5). A three-way repeated measures ANOVA revealed main effects of initial target speed $F(2,20) = 112.85$, $p \leq 0.001$, approach angle $F(1.33,13.1) = 95.26$, $p \leq 0.001$, and block $F(3,30) = 11.30$, $p \leq 0.001$. In addition, there was an interaction of initial target speed and angle on the subject's TTC $F(1.55,15.54) = 4.17$, $p = 0.044$. The main effect of initial speed simply reflects the effect of initial target speed on 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. Figure 5 shows that the effect of initial speed on subject TTC was more pronounced when the target's approach angle was smaller (corresponding to a more orthogonal trajectory), giving rise to the significant initial speed × approach angle interaction. The interaction could reflect difficulty detecting differences in initial speed when the target approached along a more head-on trajectory. When the target approaches along a more orthogonal trajectory, differences in initial speed are easy to detect because they are accompanied by salient differences in the rate at which the bearing angle changes. In contrast, when the target approaches along a more head-on trajectory, differences in the rate of change

[2] Although it is common to apply Bonferroni tests and thus to decrease alpha to compensate for the greater family-wise probability of a type 1 error when performing multiple t tests, our strategy of maintaining an alpha of 0.05 was the more conservative approach in that it increased the odds of rejecting the null hypothesis when we should not have rejected it.

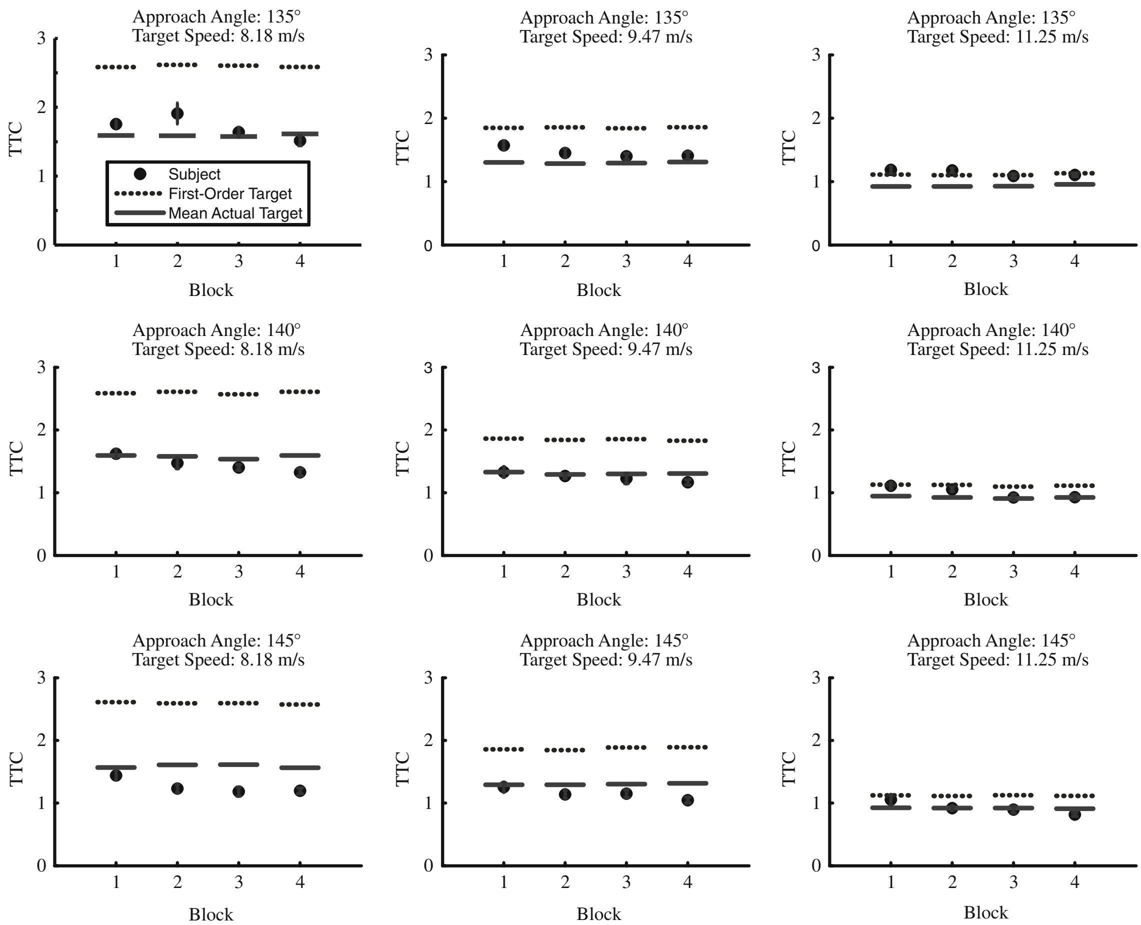


Fig. 5 Mean subject TTC, actual TTC, and first-order TTC at the onset of the change in target speed

in bearing angle across initial speeds are small. So detecting differences in initial speed requires subjects to discriminate among small differences in the optical expansion of the target. This would explain why the degree to which subject TTC varies with initial speed is less when approach angle is greater. It would also account for the largest deviation between subject TTC and actual target TTC, which occurred when initial speed was slow and approach angle was large (bottom left of Fig. 5). When subjects had difficulty perceiving initial target speed, they may have increased their speed to avoid missing the target when it accelerated. Such behavior would result in a subject TTC that was consistently smaller than actual target TTC when initial speed was slow, as in the bottom left of Fig. 5. Thus, the few situations in which subject TTC deviated from actual target TTC may be attributable to an inability to accurately anticipate the change in target speed under certain extreme conditions.

The preceding analyses indicate that subjects adopted a strategy that takes into account the behavior of the target on previous trials. In this regard, our findings are similar to those of de Lussanet et al. (2001, 2002), who found an effect of the target's speed on the previous trial on hand movements in a rapid pointing task. To further investigate this issue, we ran a follow-up analysis to determine whether subjects' strategy was based on target behavior on the most recent trial, an average of the last few trials, or an average of all trials between the first trial and the most recent trial. More specifically, this analysis provides an estimate of the number of previous trials that were taken into account when anticipating the change in target speed. For each trial, we calculated an estimate of target TTC at onset based on the assumption that the target would change to a speed equal to the mean of the final speeds on the last n trials. Hereafter, this estimate is called "windowed target TTC." Five values of n were tested: 1, 2, 4, 8, and 16. In addition, we also generated estimates based on the average of all trials that were completed up to the most recent trial. The absolute value of the difference between subject TTC at onset and each estimate of windowed target TTC was then calculated. If subjects took the last n trials into account, then the mean absolute difference between subject TTC and windowed target TTC should be least for the estimate that uses the last n trials.

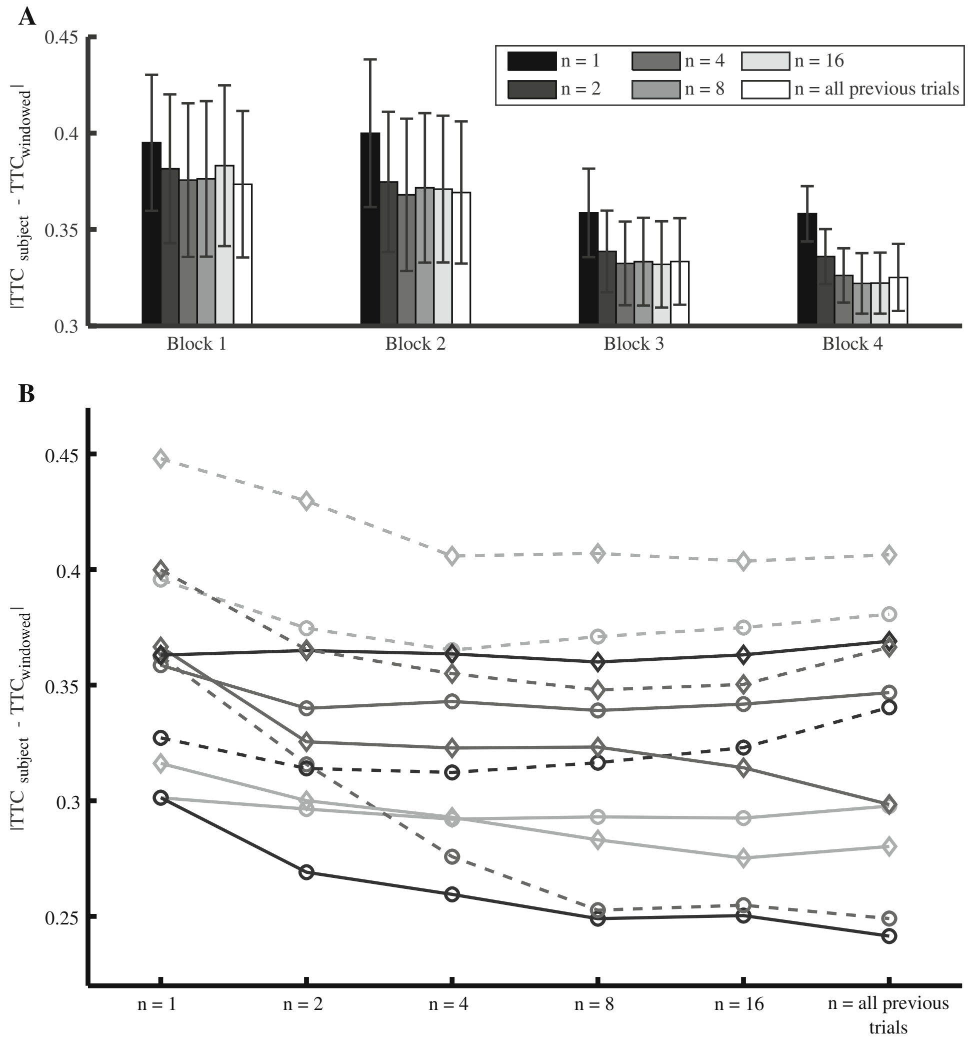


Fig. 6 **a** Mean |subject TTC—windowed TTC| for each value of n and each block. **b** Mean |subject TTC—windowed TTC| for each value of n and each subject in block 4

The results of this analysis are summarized in Fig. 6a, which shows that the mean |subject TTC—windowed target TTC| decreased as n increased up to $n = 4$, beyond which point it leveled off. This suggests that subjects took into account the behavior of the target on the last four or more trials. Because the difference did not increase for larger values of n, we cannot rule out the possibility that subjects took into account more than the last four trials. However, the fact that the difference leveled off after $n = 4$ suggests that there was no advantage in taking into account more than the last four trials. Thus, subjects were able to use previous target behavior to improve performance without having to rely on memory of target behavior in the distant past.

Given the length of the error bars in Fig. 6a, one might wonder whether this result was consistent across subjects. A closer look at the individual subject data reveals large overall differences in mean |subject TTC—windowed target TTC| (see Fig. 6b, which shows individual subject data from block 4.). However, mean |subject TTC—windowed target TTC| consistently decreased as n increased up to $n \approx 4$, confirming that the pattern was consistent across subjects.

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, our analysis of the mean subject TTC at onset indicates that behavior was influenced by the initial condition (Fig. 5), ruling out the possibility of a stereotyped approach.

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 three-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 (Fig. 4). The rate of change in bearing angle increased with both the target's approach angle $F(2,20) = 66.48$, $p \leq 0.001$, initial target speed $F(1.33,13.30) = 33.42$, $p \leq 0.001$, and block $F(3,30) = 9.47, p \leq 0.01$. There was also an interaction between angle and initial target speed $F(2.05,20.50) = 7.96$, $p \leq 0.003$, and a marginally significant interaction between initial target speed and block $F(6,60) = 2.25, p \leq 0.05$. Such variation in 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.

Summary

The results of Experiment 1 suggest that subjects did not use the constant bearing angle strategy to intercept targets that change speeds. Instead, values of subject TTC at onset more closely matched predictions that were based on accurate anticipation of the most likely change in target speed given the trial's initial conditions, as well as target behavior on the most recent four (or so) trials.

Experiment 2

Experiment 1 demonstrated that subjects were able to accurately anticipate 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 (Fig. 7).

The situation in Experiment 2 is similar to that in Experiment 1 in that use of a pure constant bearing angle strategy will often result in a failure to intercept the target. 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 Fig. 7). 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. (2006) showed that actors

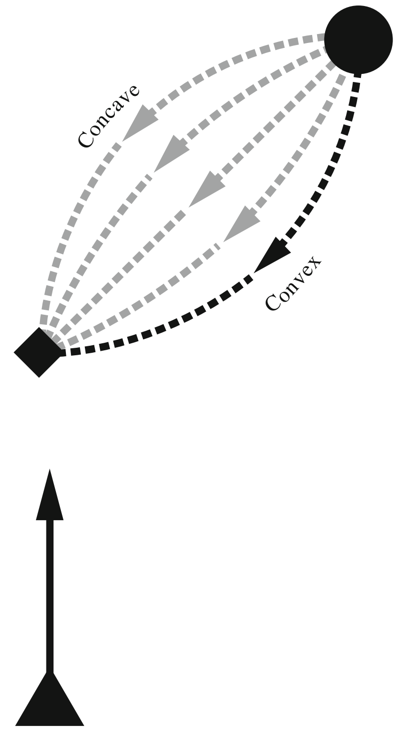


Fig. 7 An overhead view of the task in Experiment 2. The pursuer is marked by a *triangle*, and the target by a *circle*

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 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, we are able to estimate the temporal distance across which subjects are able to anticipate future target dynamics.

Methods

Participants

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

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 or 8.89 m/s, corresponding to initial time-to-contact values 4 and 4.5 s, along one of five trajectories, four of which were curvilinear, and one of which was rectilinear. The radii of the curvilinear paths were 35 or 60 m, 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) × 2 (initial target speeds) × 5 target path curvature × 5 (repetitions) × 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 Eq. 1. However, the lag coefficient was adjusted to 0.03 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.

The model

This section describes the model, and how it was used to generate predictions for different values of Δt between zero and the remaining movement time 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 $t + \Delta t$.

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:

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

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.

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)]. Our aim 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.

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 0.25 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. Because there is no advantage to predicting beyond the point of interception, Δt was adjusted on each frame after target time-to-contact dropped below Δt such that Δt equaled target TTC.

Fitting the parameters

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).[3] 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 across radius/direction pairs, but not across speeds or angles within each radius/direction pair.

The search space

The process tested each value of ω_0 between 2.5 and 4.5 in increments of 0.25. 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 0.25. The range of Δt values explored extended from 0.25 to 3.5 in increments of 0.25. The lower value of 0.03 was also included in the fitting process.

Results and discussion

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 $F(2,22) = 27.05$, $p \leq 0.01$. Repeated measures contrasts across blocks indicate that performance on block 2 was significantly different than performance on block 1 $F(1,11) = 38.18$, $p \leq 0.001$, and that performance on block 3 was significantly different than performance on block 2 $F(1,11) = 21.11$, $p \leq 0.01$. Performance also differed by radius/direction pair that defined the targets trajectory $F(2.08,22.95) = 33.40$, $p \leq 0.01$. Visual inspection of Fig. 8 suggests that performance was worst on largely convex trials, better on less convex trials, and best for rectilinear and concave curvatures. A significant interaction was found between block and curvature $F(8,88) = 3.11$, $p \leq 0.01$, possibly because improvement across blocks appears to have been greatest on conditions in which initial performance was poorest.

Speed profiles: did subjects use a predictive strategy?

Subject speed profiles will be analyzed with respect to the pure predictive strategy first, followed by the CBA and intermediate anticipatory strategies. A five-way repeated measures ANOVA was used to investigate variations of subject speed in response to changes in radius/direction pair, target approach angle, initial target speed, block, and time. Time was incorporated into the ANOVA by sampling subject speed at 1 s intervals from 0.5 s until 3.5 s into the trial.

If subjects relied on a pure prediction strategy, then subject behavior should be similar across changes in target trajectories (within each initial target speed condition). However, as one would expect based on the findings of Bastin et al. (2006), the evolution of subject velocity differed by radius/direction pair $F(12, 132) = 90.72$, $p \leq 0.01$ (Fig. 9). This is most apparent on concave trials, in which subjects accelerated in the first part of the trial before decelerating. If subjects were able to predict the future time and location of the interception point, then one would expect an initial increase in speed followed by a plateau regardless of target trajectory. Thus, the findings of Experiment 2 allow us to rule out the possibility that subjects adjusted speed based on an accurate prediction of the time and location of the interception point.

[3] 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.

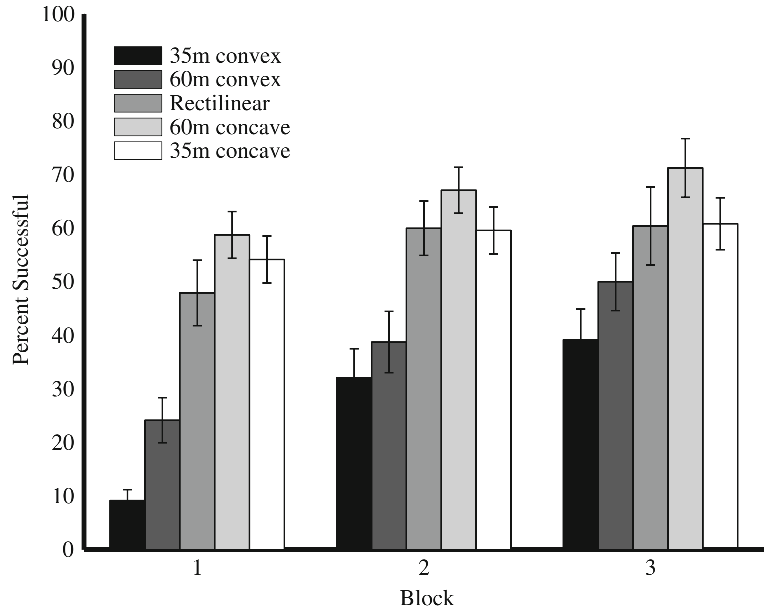


Fig. 8 Percentage of successful interceptions in Experiment 2 by block and curvature

The findings do not allow us to rule out the possibility that subjects relied upon an inaccurate prediction of the interception point. Similar velocity profiles might result from initially relying on an inaccurate prediction, and gradually refining the prediction during approach.

Speed profiles: did subjects use a CBA strategy?

The rise and fall of subject speed on concave trials is qualitatively consistent with the CBA strategy, as maintaining a CBA on such trials would require one to accelerate early on when the target's heading was roughly perpendicular to the subject's path of motion, and subsequently decelerate as the target's trajectory aligns with the subject's direction of motion. However, the anticipatory strategy with small values of Δt could also account for such behavior. The model proves useful in distinguishing between these two hypotheses. Table 1 shows the best-fitting Δt values, along with the RMSE and r^2 values, for each radius/direction pair in blocks 1 and 3, and Fig. 10 compares the simulated speed profiles (using the best-fitting parameters) with the human data for block 3. On concave trials, the best-fitting Δt values were 0.75 and 0.03 s in block 1 and 0.50 and 1.00 s in block 3, suggesting that practiced subjects adjusted speed to null the change in bearing angle 0.5–1.0 s into the future. In other words, although the rise and fall of subject speed on concave trials is qualitatively consistent with the CBA strategy, speed adjustments were better fit by the intermediate strategy with a little bit of anticipation. The good fit between the model and human data (i.e., slow RMSE values, high r^2 values) suggests that the best-fitting Δt values can be trusted as an estimate of the degree of anticipation. For the purposes of comparison, Table 1 also includes RMSE and r^2 values for both a CBA strategy ($\Delta t = 0$) and a purely predictive strategy ($\Delta t = 3.5$), neither of which fit the data as closely as an intermediate strategy ($0 < \Delta t \leq$ target TTC).

When the target follows a convex trajectory, maintaining a CBA would require one to increase speed gradually at first, and then more rapidly as the target's direction shifts from roughly parallel to the subject's path to roughly perpendicular. Although subject speed increased throughout the trial, the majority of acceleration took place early in the trial rather than later, and velocity changed little towards the end of the trial when the change in bearing angle was greatest (see Fig. 9). This suggests that subjects learned to anticipate the predictable evolution of the target's trajectory. Not surprisingly, the best-fitting values of Δt were quite high (3.5 s), and when Δt was set to 0.03, performance was quite poor (see Table 1). This might be interpreted as evidence that subjects were able to anticipate further into the future on convex trials. However, it is not clear why subjects would be able to anticipate further into the future on convex trials compared to concave trials. Furthermore, the poorer quality of fit on convex trials (see Table 1, Fig. 10) raises some concerns about the reliability of the high Δt value as an estimate of the degree of anticipation. In particular, Fig. 10 suggests that the model with $\Delta t = 3.5$ s captured speed adjustments during the first 2 s, but not during the latter part of the approach. After the first 2 s, the model's speed consistently exceeded subject speed, suggesting that subjects did not look ahead as far as $\Delta t = 3.5$ suggests. One alternative explanation for the inflated Δt values is that subjects accelerated more than necessary during the first part of the trial to avoid the

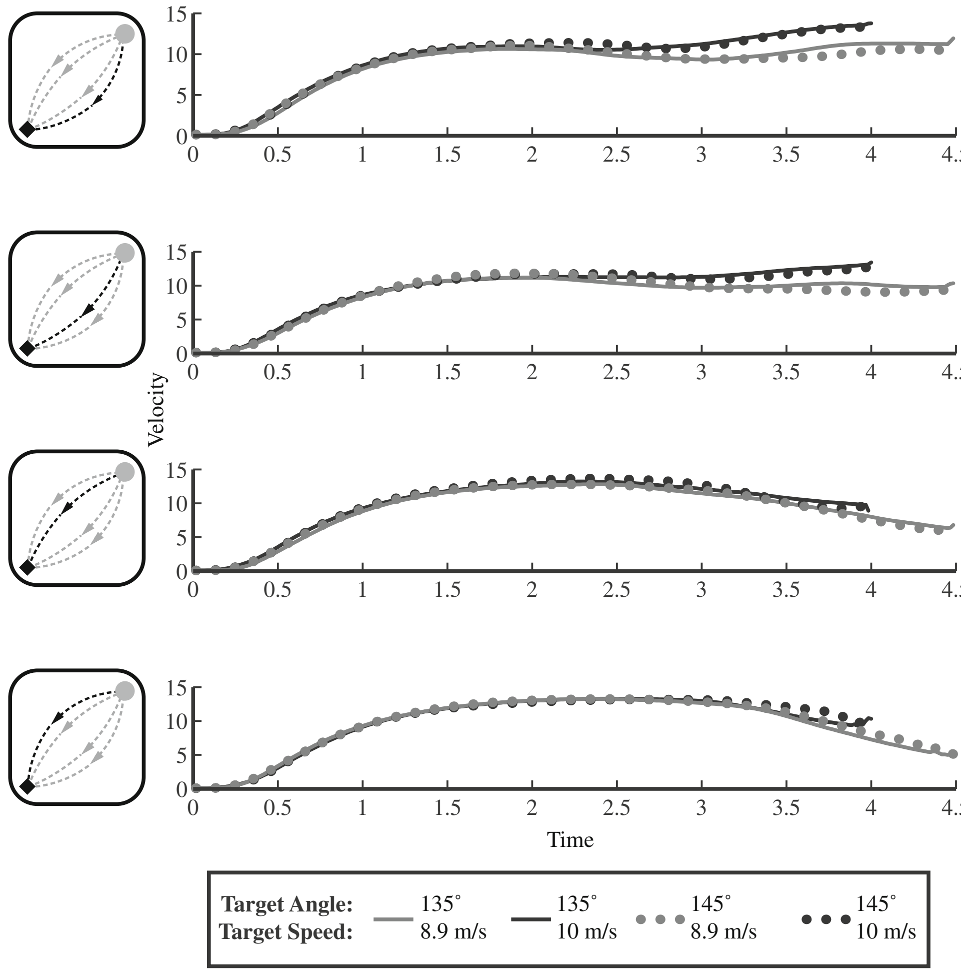


Fig. 9 Mean subject velocity over time for block 3 of Experiment 2. Each *panel* corresponds to a different target trajectory. Within each panel, velocity profiles are broken down by angle and speed

situation in which the speed needed to intercept the target exceeded the maximum possible speed. Because the best-fitting parameters were chosen based on the entire trajectory, the estimate of Δt may have been inflated by behavior during these first 2 s. Whether the observed values of Δt accurately reflect the temporal distance of anticipation, or a difficulty for the model to account for adjustments early in the trial, behavior was clearly inconsistent with the CBA strategy on both convex and concave trials.

One might wonder whether different results would be obtained if the procedure used to estimate Δt was based on successful trials only. The concern is that what appears to be a strategy of anticipating target behavior a brief period into the future might actually result from anticipating farther into the future and occasionally being wrong about the target's behavior. Assuming that subjects were less likely to intercept the target when they inaccurately anticipated target behavior, excluding unsuccessful trials might yield a different estimate of Δt. To investigate this possibility, we isolated successful trials and re-fit the model. Successful trials from blocks 2 and 3 were pooled to increase the number of data points. Only minor differences were found between the best-fitting parameters for successful trials and those for both successful and unsuccessful trials. The best-fitting values of frequency (3.75) and damping (12.19) were only slightly different for those when the model is fit to all trials (see Table 1 for values for all trials). Values of Δt were identical with the exception of the 60 m concave trajectory, in which Δt was 1.25 compared to 0.5 s for the analysis with all trials. Thus, we can rule out the possibility that the evidence for an intermediate anticipatory strategy resulted from including both successful and unsuccessful trials.

Speed profiles: effects of target speed and approach angle

Subject speed profiles within each radius/direction pair were also grouped according to initial target speed, and unaffected by approach angle (see Fig. 9). An interaction of sample and initial target speed was found $F(3,33) = 107.84$, $p \leq 0.01$, whereas none was found between sample and approach angle $F(3,33) = 1.61$, $p = 0.21$. The significant sample $\times$ initial target speed interaction simply captures the fact that subjects

Table 1

Block 1: $\omega_0 =$ 3.25 $\beta =$ 10.56			
Radius/direction	RMSE	*r2*	Δt (s)
35 m, convex	1.55	0.93	3.5
60 m, convex	1.22	0.95	3.5
60 m, concave	0.61	0.98	0.75
35 m, concave	0.88	0.96	0.03
Block 3: $\omega_0 =$ 3.75 $\beta =$ 12.19			
Radius/direction	RMSE	*r2*	Δt (s)
35 m, convex	1.12	0.94	3.5
60 m, convex	1.2	0.91	3.5
60 m, concave	0.5	0.98	0.5
35 m, concave	0.89	0.95	1
Block 3: $\omega_0 =$ 3.75 $\beta =$ 12.19 (fixed Δt)			
Radius/direction	RMSE	*r2*	Δt (s)
35 m, convex	3.37	0.65	0.03
60 m, convex	2.28	0.69	0.03
60 m, concave	0.66	0.97	0.03
35 m, concave	1.09	0.95	0.03
Block 3: $\omega_0 =$ 3.75 $\beta =$ 12.19 (fixed Δt)			
Radius/direction	RMSE	*r2*	Δt (s)
35 m, convex	1.12	0.94	3.5
60 m, convex	1.20	0.91	3.5
60 m, concave	1.92	0.75	3.5
35 m, concave	1.87	0.77	3.5

must travel faster to intercept faster targets. The non-significant sample x approach angle interaction is also adaptive, as the target reaches the interception point at the same time regardless of approach angle.

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 (Fig. 10). Like the subject data, the simulated velocity profiles were unaffected by the initial approach angle.

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. In most conditions, 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 regularities in the target's behavior to anticipate the most probable change in target speed. Importantly, our findings are inconsistent with the conclusions of other papers on interception (e.g., Chardenon et al. 2005), according to which actors continue to use the CBA strategy even when target speed and/or direction changes.

Whereas, in Experiment 1, the change in the target's trajectory occurred over a short duration (0.5 s), targets in Experiment 2 approached along curvilinear paths, causing a continuous change in trajectory throughout the trial. Although these simple and continuous changes in target trajectory would seem ideal for a predictive model of interception, Bastin et al. (2006) 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. We extend this research by considering intermediate strategies, by which subjects anticipate the change in target behavior and adapt their speed accordingly to null the change in bearing angle a short time into the future.

As in Bastin et al. (2006), the trajectory of the target significantly affected behavior, ruling out the predictive strategy. Although speed profiles were affected by target trajectory, the differences were not as great as one would expect based on a CBA strategy. To further investigate intermediate strategies involving anticipation of target behavior a brief period into the future, human behavior was compared to a model that, at each time *t*, makes an adjustment that nulls the change in bearing angle at the future time $t + \Delta t$. When the target followed a concave trajectory, the model best fit the human data using intermediate values of Δt. For convex trajectories, higher values of Δt best fit the human data. However, these values may have been inflated by the initial speed adjustment. Taken together, behavior was consistent with neither a pure predictive strategy nor a CBA strategy, and was best captured by an intermediate strategy that allows for some degree of anticipation.

From feedback to anticipation

Our conclusions are consistent with certain aspects of *information-based control* (Warren 1998), according to

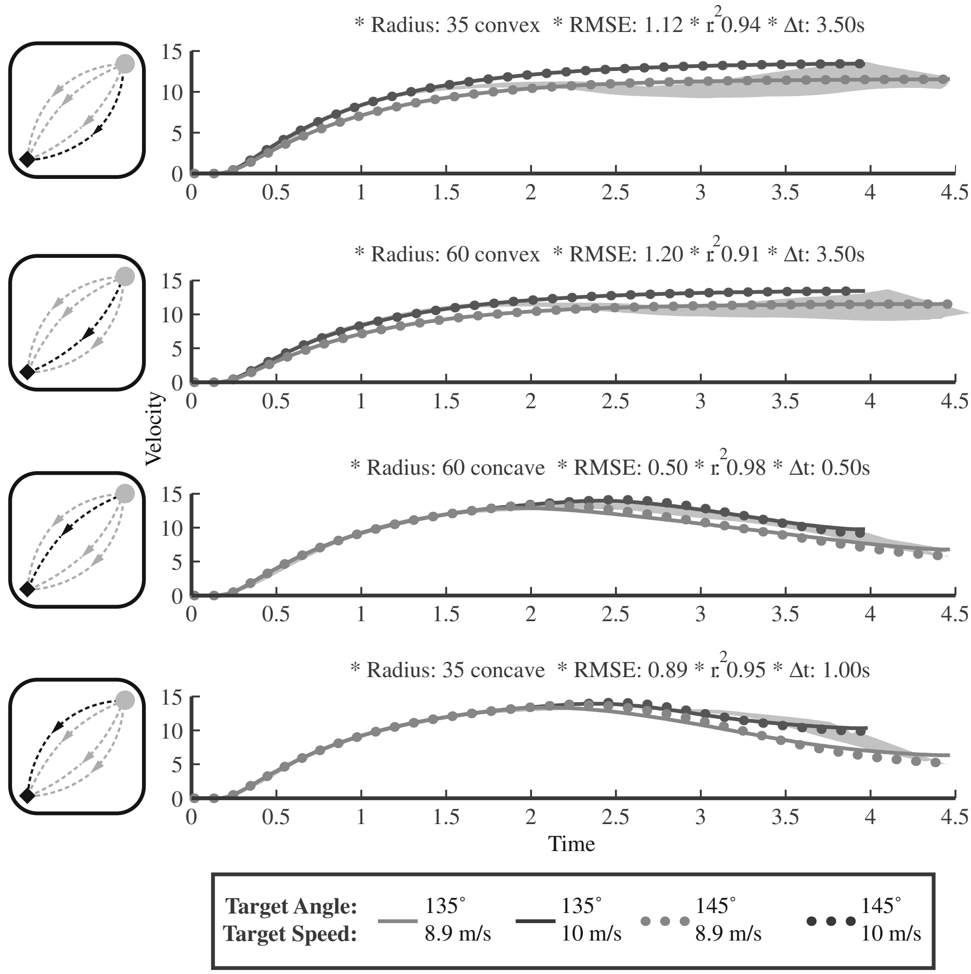


Fig. 10 Mean simulated velocities (*lines* and *circles*) for block 3 of Experiment 2 overlaid upon subject velocity (*shading*). Each *panel* corresponds to a different target trajectory. Within each panel, simulated velocity profiles are broken down by angle and speed

which action is coupled to information in optic flow according to a law of control. Consistent with Warren's definition, our 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 most 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 one form of learning that is not typically considered in theories of information based control: the actor must learn how to choose an appropriate action that will bring about the desired change in the relevant optical variable(s). 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). Whatever framework is chosen, the results of Experiments 1 and 2 suggest that the solution must take into account the likely target behavior based on both past experience and currently available information. However, additional research is required to address the issues of how and which aspects of past experience are factored in. One approach would be to build upon what was done in the present study by developing more sophisticated models that allow one to generate predictions by changing the way in which past experience is taken into account. For example, to the degree that actors optimally weight past experience based on the consistency of target behavior and currently available information based on its reliability, a Bayesian approach may be best suited to capture behavior. Alternatively, if past experience and current information are not optimally integrated, then simpler models may be sufficient.

The proposed 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). The 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 additional explanatory power by, for example, accounting for how movements are guided during brief periods of interrupted visual feedback. If the actor knows how to move so as to bring about a desired change in optic flow, then movement can still be guided (albeit not as effectively) even when vision is temporarily occluded.

Acknowledgment This research was supported by grants from the National Science Foundation (BCS 0545141 and BCS 0236734)

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