Exp Brain Res (2010) 201:763–780
DOI 10.1007/s00221-009-2092-y

RESEARCH ARTICLE

# Controlling speed and direction during interception: an affordance-based approach

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Received: 24 February 2009 / Accepted: 10 November 2009 / Published online: 1 December 2009


**Abstract** The coordination of direction and speed of self-motion when intercepting a target moving parallel to the ground plane was examined. Subjects viewed a computer-generated environment comprised of a textured ground plane and a moving target. Turning rate was controlled using a steering wheel and speed was controlled using a foot pedal. It was hypothesized that these two degrees of freedom would be coordinated such that the speed required to intercept the target (i.e., the ideal speed) would be maintained below the subject's maximum possible speed. As predicted, subjects turned toward the target when ideal speed was less than maximum speed and ahead of the target when ideal speed was greater than maximum speed. When behavior was compared across groups with different maximum speed capabilities, it was found that the ratio of ideal to maximum speed was invariant across groups at critical points of both steering and speed adjustments. Finally, subjects rapidly recalibrated to a sudden increase or decrease in maximum speed. The results suggest that actors coordinate steering and speed during interception in a way that takes into account the limits on their action capabilities. Discussion focuses on the role of calibration and the implications of the present findings for existing models of visually guided interception.

**Keywords** Visually guided locomotion · Interceptive actions · Perceptual-motor calibration · Steering · Affordance perception

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## Introduction

To successfully intercept moving targets, actors must coordinate their movements on the basis of visual information in such a way as to satisfy repeatedly demanding spatiotemporal constraints (see Zago et al. (2009) for a comprehensive review). Research on locomotor interception has led to the formulation and testing of laws of control (Warren 1998) that formalize how information variables are linked to action variables. Such control laws capture the tight coupling between information in optic flow and movement that is characteristic of visually guided interception. Like models of other visually guided actions, such as steering (Wann and Land 2000), braking (Lee 1976; Yilmaz and Warren 1995), and fly ball catching (Chapman 1968; Michaels and Oudejans 1992; McLeod et al. 2006), existing models of locomotor interception share the common assumption that the control of action is *prospective*, i.e., based on information about one's future assuming current conditions persist (Montagne 2005; Fajen 2005b). Such information tells the actor about the sufficiency of his or her current state relative to the task requirements. Hence, the only thing one has to do to succeed is to move in such a way that the information specifies that the current state is sufficient. Once the observer is in this ideal state, he or she can perform the task successfully by simply maintaining that state.

The motivation for the present study was that existing prospective control models fail to explain two important aspects of locomotor interception: (1) how steering and speed are coordinated, and (2) how actors move in ways that take the limits of their action capabilities into account. We hypothesize that actors are sensitive to the limits of their locomotor capabilities, and that such sensitivity serves as an important constraint in the coordination of steering and speed. We then present the results of one experiment designed to test predictions that follow from the hypothesis that steering and speed are coordinated in a way that takes into account the limits of one's locomotor capabilities.

## Behavioral strategies for intercepting moving targets on foot

Let us begin by describing how the principle of prospective control has been applied to the task of intercepting a moving target on foot.

### *The constant bearing angle (CBA) model*

A simple heuristic for intercepting a moving target is to move in such a way as to maintain a constant bearing angle (e.g., Lenoir et al. 2002; Chardenon et al. 2004; Fajen and Warren 2004, 2007). The bearing angle is defined by the direction of the target relative to some fixed exocentric reference direction (see Fig. 1).[1] The key to the constant bearing angle (CBA) model is the invariant relationship between the direction of change in bearing angle (positive or negative), and the sufficiency of the actor's current velocity. Whenever the bearing angle decreases, current velocity is insufficient and the actor should either accelerate or turn ahead of the target. Whenever the bearing angle increases, current velocity is excessive and the observer should either decelerate or turn in the direction of the target. Thus, the first derivative of the bearing angle provides information for prospective control, in the sense that it directly specifies the sufficiency of the actor's current speed and direction.

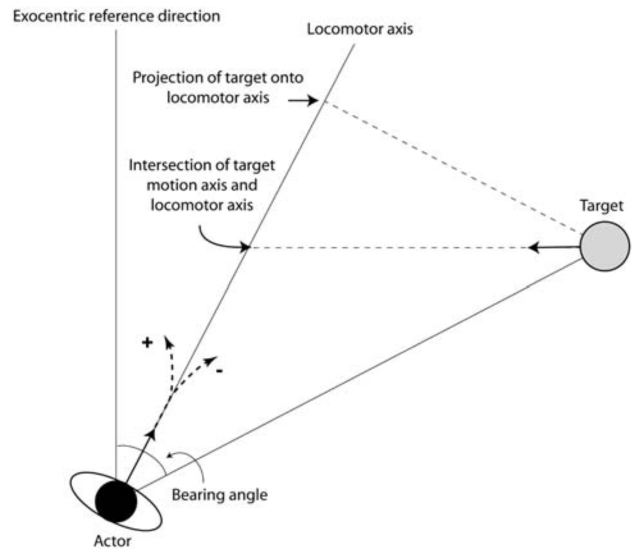


**Fig. 1** Schematic representation of interception task. The bearing angle is the angle of target with respect to an exocentric reference direction. The locomotor axis is defined by the actor's instantaneous direction of locomotion

### *The required velocity (RV) model*

An alternative to the CBA model is the required velocity (RV) model, which was originally proposed by Peper et al. (1994) to account for lateral hand interception, and subsequently tested as a model of locomotor interception by Chardenon et al. (2002). The RV model is designed to capture the visual control of speed under situations in which the hand or body is constrained to move along a fixed displacement axis. The required velocity is defined as the ratio of the distance between the actor and the projection of the target onto the actor's locomotor axis to the target's time-to-contact (TTC) with the locomotor axis (see Fig. 1). Like the change in bearing angle, the difference between the actor's current velocity and the required velocity provides information for prospective control in that it tells the actor about the sufficiency of his or her current velocity. When current velocity is less than required velocity, the actor needs to accelerate to intercept the target; when current velocity is greater than required velocity, the actor needs to decelerate to intercept the target.

Although the CBA and RV models differ in terms of the relevant optical information, both share the same underlying logic—they describe how the interception task can be performed on the basis of information about the sufficiency of the actor's current velocity. Furthermore, they characterize changes in speed and direction as error-nulling adjustments that cancel the difference between the current and ideal states. In the next section, we will point out the limitations of these models, and introduce an alternative

[1] Maintaining a constant egocentric (rather than exocentric, e.g., Bastin et al. 2006) target angle will also bring about interception as long as the body is aligned with the direction of locomotion. However, for certain initial conditions, this strategy will result in approach trajectories that spiral around the target, with the instantaneous direction of locomotion lagging behind the target by a fixed angle (Fajen and Warren 2007). Such trajectories differ from those produced by humans, who converge onto a linear path with the direction of locomotion leading the target (Fajen and Warren 2004). Hence, the constant bearing angle strategy is better characterized in terms of maintaining a constant exocentric target direction. The change in bearing angle may be estimated on the basis of the change in target direction relative to a distant landmark, or by subtracting an estimate of body rotation from the change in egocentric target direction (Fajen and Warren 2007).

approach that offers a first step toward addressing these limitations.

## Limitations of the CBA and RV models

### *Coordination of steering and speed*

Most real-world interception tasks are two degree-of-freedom control tasks in that actors can change either direction or speed of locomotion (or both) to intercept the target. Neither the CBA nor the RV model provides a suitable account of how these two degrees of freedom are coordinated during interception. According to the CBA model, a change in bearing angle specifies that the actor should change either speed or direction (or both). However, this model makes no predictions about when actors will change direction only, when they will change speed only, and when they will change both direction and speed. The RV model freezes one of the degrees of freedom (direction), simplifying the problem to a one degree-of-freedom control task and ruling out the possibility of intercepting targets by turning (but see Montagne et al. (2004) for a tentative development of the RV model).

As most of the empirical studies of locomotor interception have been framed by either the CBA or RV model, experiments in these studies were not designed to shed light on the coordination of steering and speed. In many experiments (e.g., Chardenon et al. 2002, 2004; Lenoir et al. 2002; Bastin et al. 2006), subjects intercepted targets by making speed adjustments while their movements were constrained to a single direction. In other studies (e.g., Fajen and Warren 2004), speed was partially constrained by instructing subjects to walk at a normal pace. One of the goals of the present study was to take a first step toward understanding how steering and speed are coordinated when both degrees of freedom can be controlled.

Although the coordination of steering and speed during locomotor interception remains an open question, the strategies used to manually intercept moving targets (e.g., when catching a ball by hand) in two dimensions is better understood. One general principle from the study of manual interception is that people increase hand movement speed as the temporal accuracy demands of the task increase, which can result from an increase in target speed or a decrease in target or end-effector (e.g., hand or bat) size (Brouwer et al. 2005; Tresilian and Lonergan 2002; Tresilian and Houseman 2005; Tresilian et al. 2004). The benefit of this strategy follows from the well-documented finding that faster movements are associated with lower temporal variability (see Schmidt and Lee (2005) for a review).

Second, when the hand is allowed to move in more than one dimension such that the location of the interception point is not predetermined, then the task requires both spatial and temporal precision. Whereas temporal precision improves when movement speed is fast, spatial precision improves when movement speed is slow, reflecting the well-known speed-accuracy tradeoff (Fitts and Peterson 1964; Schmidt and Lee 2005). Thus, improving temporal accuracy can be achieved by moving faster, but at the cost of spatial accuracy. This means that a compromise must be found between maximizing temporal precision by moving quickly and maximizing spatial precision by moving slowly. Indeed, under some conditions in which hand movements are not constrained to a single dimension, movement time increases when target size decreases, suggesting that the greater spatial precision demands associated with smaller targets are satisfied by slowing down (Brouwer et al. 2005; Tresilian et al. 2009).

A third principle revealed in studies of manual interception is that the direction and speed (or acceleration) of the hand are independently controlled (Smeets and Brenner 1995; Brenner and Smeets, 1996; Brenner et al. 2002). This was demonstrated by showing that biasing the perceived target velocity by displacing the background to induce relative motion influences hand acceleration but not direction (Smeets and Brenner 1995). Similarly, the initial acceleration of the hand was only weakly correlated with its initial direction (Brenner et al. 2002).

The degree to which these principles apply to locomotor interception is not known. One important difference between the manual interception of rapidly moving targets and locomotor interception is that movement duration is significantly longer during locomotor interception. The longer duration allows for the use of visual information to make on-line adjustments. So, some of the movement regularities that underlie the aforementioned principles (e.g., temporal variability decreases as movement speed increases) may not apply. Thus, although there are similarities between manual interception and locomotor interception, the set of constraints for these two actions are not exactly the same. In the next section, we discuss one constraint that is especially relevant to locomotor interception, and may provide important clues about how speed and direction are coordinated.

### *The maximum speed constraint*

A second weakness of the CBA and RV models is that they ignore the fact that there are limits to how fast actors can move and how quickly they can turn. One might attempt to address this weakness by simply adding a constraint to the model that limits the agent's speed and turning rate. For example, in the servo-control model of projectile interception proposed by Tresilian (1995), a performance limit parameter acts as an external constraint on the controller output that limits the actor's speed and acceleration. This prevents the model from allowing unrealistic movements that lie beyond the actor's locomotor capabilities. However, including performance limits as external constraints does not address the more significant problem of how actors control their movements in a way that takes their limits into account. Consider, for example, the situation in which a target is moving from right to left as in Fig. 1. Let us define the *ideal speed* as the speed required to intercept the target without changing direction. In terms of spatial variables, ideal speed is equal to the distance from the actor to the point of intersection between the target motion and locomotor axes (see Fig. 1) divided by the time-to-contact the target with the locomotor axis.[2]

Suppose the actor's current speed is less than ideal speed such that the target will pass in front of the actor if current speed and direction are maintained. If the actor accelerates soon enough, then it may be possible to intercept the target without changing directions. However, if the actor waits too long before accelerating, then ideal speed will eventually exceed the maximum speed that the actor can (or is willing to) achieve, at which point the target is no longer catchable (at least without changing direction). Thus, an actor's maximal possible (or comfortable) speed introduces an important constraint that determines whether or not it is within the actor's capabilities to intercept the target. Actors must be sensitive to their maximum speed capabilities and take them into account to effectively and efficiently coordinate steering and speed control when intercepting moving targets. Unfortunately, neither the CBA model nor the RV model can explain how actors take their speed capabilities into account because these models either ignore the fact that such limits exist or treat them as post hoc external constraints.

Some insights into how actors take their limits into account during interception might be gleaned from studies of a different kind of visually guided action—specifically, visually guided braking (Fajen 2005a, c). In these studies, participants performed a simulated braking task that required them to modulate deceleration by adjusting the position of a foot pedal so as to come to a stop as close as possible to a row of stop signs. Simulated deceleration was proportional to the position of the foot pedal, such that participants coasted when the pedal was released and decelerated at the maximum rate when the pedal was completely depressed. In the context of the braking task, the relevant control variable is deceleration and the relevant performance limit is the maximum rate of deceleration. Thus, actors must modulate current deceleration in such a way that the deceleration required to stop (i.e., ideal deceleration) remains below maximum deceleration.[3] If ideal deceleration exceeds maximum deceleration, then it is no longer possible to avoid a collision by braking. As one would expect, braking behavior is quite variable when ideal deceleration is well below maximum deceleration (Fajen 2005a). The likelihood of increasing, decreasing, and maintaining deceleration is roughly equal in these situations. However, as ideal deceleration approached maximum deceleration, actors almost always increase deceleration or slam on the brakes. Such behavior is exactly what one would expect from a strategy of keeping ideal deceleration within the safe region below maximum deceleration. In a follow-up study, Fajen (2005c) manipulated the strength of the brake as a between-subjects factor and compared performance across groups. Subjects who were calibrated to the weaker brake tended to increase deceleration at lower values of ideal deceleration. In comparison, those who were calibrated to a stronger brake tolerated higher values of ideal deceleration before initiating an increase in braking. When ideal deceleration at the onset of brake adjustments was expressed as a percentage of maximum deceleration for groups with different brake strengths, it was invariant across groups. Taken together, these findings provide strong evidence that actors behave in ways that take the limits of their action capabilities into account.

To explain these results, Fajen (2005a, b, c) proposed that actors make adjustments, not to cancel the difference between the current and ideal deceleration, but rather to keep ideal deceleration below maximum deceleration, which can be considered a "safe region". As long as ideal deceleration is below maximum deceleration, it is still within the actor's capabilities to avoid a collision by braking; that is, safe stopping is still possible. If, at any point, ideal deceleration exceeds maximum deceleration, then it is no longer within the actor's capabilities to avoid a collision by braking; safe stopping is not possible. Thus, keeping ideal deceleration below maximum deceleration is both a necessary and sufficient condition for success in the braking task. In the next section, we show how applying the same logic to the interception task suggests a way in which steering and speed might be coordinated during interception.

[2] Ideal speed is the same as required speed in the RV model of interception. We prefer the former term because the actor is not, in fact, required to maintain that speed throughout the entire approach. There are an infinite number of other speed profiles that also allow for successful interception. On the other hand, ideal speed is "ideal" in the sense that the actor moving at this speed can intercept the target without making any further changes to speed or direction.

[3] This is analogous to the way in which actors trying to intercept a moving target must modulate current speed to keep ideal speed below maximum speed.

## A new hypothesis about the coordination of speed and direction

Recall that ideal speed corresponds to the speed required to intercept the target without changing direction. The basic hypothesis that we test in this study is that actors will coordinate steering and speed in such a way as to keep ideal speed below the maximum speed that they can (or are willing to) produce. When ideal speed is less than maximum speed, it is within the actor's capabilities to intercept the target by adjusting speed without changing direction. Thus, the actor can intercept the target by making speed adjustments that continue to keep ideal speed between minimum and maximum speed. Of course, the actor may try to intercept the target sooner by turning in the direction of the target while adjusting speed. However, turning in the direction of the target increases ideal speed, which requires the actor to move faster to intercept the target than if current heading was maintained. Actual behavior in this situation is likely to depend on various factors, such as the costs associated with intercepting the target later rather than sooner, and the effort associated with moving at faster speeds. If there is no advantage to intercepting the target quickly and if the actor is fatigued, then he or she may continue to move in the same direction and intercept the target while moving at a slower speed. On the other hand, if there is an advantage to intercepting the target sooner (e.g., when a defender must tackle the ball carrier in sports such as rugby or American football), then the actor may turn toward the target while accelerating. In the present study, subjects performed an interception task in a simulated environment, where faster speeds could be achieved without additional effort. Furthermore, subjects were instructed to intercept the target quickly (while still maintaining accuracy). Hence, we expected that subjects in the present study would behave like the defenders in football, turning toward the target and accelerating when ideal speed was less than the maximum speed.

Now consider the situation in which ideal speed exceeds maximum speed. In this case, it is no longer possible to intercept the target by adjusting the speed of travel alone. However, one may still be able to intercept the target by turning ahead of the target. This works because turning ahead of the target decreases ideal speed. So, as long as the observer can turn quickly enough, it will once again be possible to intercept the target by adjusting speed within the limits of the observer's capabilities. Thus, the prediction is that subjects will increase speed and turn ahead of the target as ideal speed approaches maximum speed. Furthermore, the moment at which actors turn ahead of the target should depend on their speed capabilities. Specifically, actors who cannot move quickly should turn sooner (i.e., at lower values of ideal speed) compared to actors who can move quickly. Finally, as speed capabilities are not fixed and in some cases can change quite rapidly (e.g., as a result of injury or changes in surface traction), actors must be able to rapidly recalibrate to changes that affect their maximum possible speed. Thus, if maximum speed suddenly increases (or decreases), the critical value of ideal speed at which actors turn ahead of the target should also increase (or decrease).

To summarize, the aim of the present study is to test the following predictions: (1) when ideal speed is less than maximum speed, subjects will increase speed and turn toward the target; (2) when ideal speed is greater than maximum speed, subjects will increase speed and turn ahead of the target; (3) the critical value of ideal speed at which subjects turn ahead of (rather than toward) the target will be greater for faster subjects and less for slower subjects; (4) when this critical value of ideal speed is expressed in intrinsic units (i.e., as a percentage of subjects' maximum speed), it will be invariant across groups just as ideal deceleration at brake onset was invariant across groups in Fajen (2005c); (5) subjects will be able to rapidly adapt to changes that affect their speed capabilities.

To test these predictions, subjects watched displays simulating self-motion through a simulated environment, with a spherical target moving above a textured ground plane at eye level. Subjects were instructed to intercept the target by using a steering wheel to adjust path curvature and a foot pedal to adjust speed. Three groups of subjects completed 10 blocks of 20 trials. Maximum speed was manipulated as a between-subjects factor with three levels: slow (5 m/s), medium (7 m/s), and fast (9 m/s). After four blocks of trials, maximum speed changed for the slow and fast groups such that all three groups have the same maximal speed (7 m/s). This second phase of the experiment was included to test subjects' ability to recalibrate to new speed capabilities.

# Methods

## Subjects

Thirty students (6 females and 24 males; average age 18.7 ± 0.9 years) participated in the experiment. One-third of the subjects were randomly assigned to each maximal speed condition. All had normal or corrected-to-normal vision.

## Displays and apparatus

Displays were generated using OpenGL running on a Dell Precision 530 Workstation, and were rear-projected by a Barco Cine 8 CRT projector onto a large (1.8 m × 1.2 m)

**Fig. 2** Representation of the virtual reality setup used (*left*) and sample frame from the display used in the experiment (*right*)

screen at a resolution of 1,280 × 1,024 and a frame rate of 60 Hz. The border of the projection screen and the surrounding walls were covered with a black felt fabric to reduce the salience of the screen frame. The displays simulated a spherical target (0.3 m in diameter) moving at eye level over a textured ground surface. The target always moved from right to left, and started at a constant initial bearing angle of 45°. The sky was light blue, and the ground texture was grassy green and 1.1 m below the subject's viewpoint (Fig. 2).

Steering and speed were controlled using a ECCI Trackstar 6000 steering wheel/foot pedal system. Subjects increased speed by pushing the pedal from the neutral initial position. The pedal was programmed so that speed was proportional to pedal position. Speed ranged from 1 to 5 m/s (slow condition), 1.4 to 7 m/s (medium condition), and 1.8 to 9 m/s (fast group). The foot pedal was spring-loaded to provide resistance to displacement that was approximately proportional to displacement from the neutral position. The steering wheel was programmed so that the path curvature was proportional to steering wheel angle. Maximum path curvature (7.5°/m) was constant across the three groups to mimic similar steering capabilities of vehicles that differ in maximum speed only. Foot pedal and steering wheel positions were sampled at 60 Hz and used to update the display with a loop time of 1 frame.

There were 5 target speeds (3.21, 3.57, 3.93, 4.29, and 4.64 m/s in the slow speed condition, 4.5, 5, 5.5, 6, 6.5 m/s in the medium speed condition, and 5.8, 6.4, 7.1, 7.7, 8.4 m/s in the fast speed condition), two target approach angles (±5° relative to orthogonal), and two initial distances between the subject and the target (14.3 and 21.4 m in the slow speed condition, 20 and 30 m in the medium speed condition, and 25.7 and 38.6 m in the fast speed condition). By varying the initial conditions, the difficulty of the task was comparable across groups (pilot studies were conducted to determine initial conditions that would result in similar task difficulty). If the initial conditions were the same, the task would have been either too difficult for subjects in the slow group or too easy for subjects in the fast group. Minimum observer speed, initial distance, and target speed were scaled across groups in such a way that initial ideal speed expressed as a percentage of maximum speed was the same for each combination of initial target speeds and initial distance for all three groups.[4]

Procedure

Subjects sat in front of a large screen at a distance of 1 m (85° × 62° field of view). They were instructed to intercept the moving target as fast as they could by using the steering wheel and the foot pedal to change their path curvature and their speed of approach, respectively. Specific instructions were given to encourage smooth steering and speed changes, and to avoid sudden or jerky steering and speed adjustments that would be uncomfortable and unsafe in the real world (see Fajen (2005a, c) and Yilmaz and Warren (1995) for a similar procedure).

Trials were initiated by pressing a trigger button on the steering wheel while the foot pedal was in the neutral position. The scene containing the moving target appeared and simulated forward self-motion at the minimum speed began immediately. Displays ended when the subjects' distance to the target was <0.5 m or when this distance increased for several seconds, which occurred when the subject missed the target and was unable to catch up to it again. To indicate that a collision with the target occurred, an audio signal was played. Prior to the experiment, subjects completed a practice session consisting of 200 trials under the same conditions used in the experiment.

[4] Initial (scaled) ideal speed range used was comprised between 58.3 and 100% (the whole range of values used was 58.3, 64.9, 69.5, 71.4, 77.3, 78, 84.4, 85.1, 92.9, and 100%). This range was identical for the two initial distances used, which therefore leads to 20 initial conditions; however, note that if subjects were maintaining the initial speed, ideal speed increased more rapidly for the shorter initial distance.

## Design

The design of the experiment was 3 (maximal speed) × 5 target speed × 2 initial distance × 2 target angle of approach. Maximal speed was a between-subjects factor, and the other factors were within-subject factors. One trial per condition was presented within each block for a total of 20 trials per block. Ten blocks were presented for a total of 200 trials. On the first four blocks, maximal speed varied between groups (5, 7, and 9 m/s). On the last six blocks, maximum speed was 7 m/s for all three groups, which provided a test of recalibration to new action capabilities for subjects of the slow and fast conditions. Subjects were not informed that maximal speed changed during the experiment. The entire experiment lasted for approximately one hour.

## Data analysis

During each trial, the computer recorded the position and speed of the subject and the position of the target in the virtual world at 60 Hz. We used two measures of success: percentage of successful trials and final temporal error. Final temporal error was estimated by first measuring final spatial error, which was calculated using the extrapolated positions of the subject and the target, assuming a straight path for the subject (recall that the display stopped as soon as the subject–target distance was below 50 cm). Final temporal error was then computed by dividing the final spatial error by the difference between the subjects' final speed and the target speed.

Individual adjustments to speed and steering were identified using an algorithm that was written to find transition points (i.e., starts, stops, and reversals) in the curvature and speed time series (see Yilmaz and Warren (1995) and Fajen (2005a, c) for a similar procedure). Data from two sample trials are shown in Fig. 3 to illustrate the procedure. We chose to use the curvature time series (i.e., the steering rate of change divided by the tangential speed of travel) to identify the turning adjustments because maximum curvature was held constant across groups. Starts (designated by filled circles in Fig. 3) were recorded when the observer increased or decreased curvature by at least 5% of maximal curvature for 200 ms or more. Curvature adjustments that resulted in changes in curvature of <5% of maximal curvature or that lasted <200 ms were not counted. Similarly, starts in the speed time series (filled squares in Fig. 3) were recorded when the speed increased or decreased by >5% of maximal speed, and lasted >200 ms, while changes of <200 ms or <5% of maximal speed were not counted. Stops (open circles and squares in Fig. 3) were recorded when the observer stopped moving the gas pedal or the steering wheel such that curvature or speed were held constant (i.e., were held at a value <1% of maximal possibilities) for 200 ms. Reversals were recorded when the observer reversed the direction of motion of the steering wheel or the gas pedal such that curvature (speed) at the reversal point was at least 2.5% of maximal capabilities greater than (for a ∩-shaped reversal) or less than (for a U-shaped reversal) curvature (speed) at the beginning and the end of a 200 ms window surrounding the reversal point. Individual curvature and speed adjustments were identified by looking for starts followed by stops or reversals followed by stops or reversals (dotted lines in Fig. 3). An adjustment was considered positive when it resulted from a turn ahead of the target or an increase in speed, and negative when it resulted from a turn toward the target or a decrease in speed (see + and − signs in Fig. 1). Positive adjustments resulted in a decrease in ideal speed and negative adjustments resulted in an increase in ideal speed. Recall that ideal speed was computed by calculating the distance from the subject to the point of intersection between the target motion and locomotor axes, divided by the time-to-contact of the target by the locomotor axis. This calculation was made at each frame to arrive at a time series for ideal speed (see Fig. 3d). The frames on which steering and speed adjustments were initiated were then used to determine the ideal speed at the onset of each individual adjustment.

The critical value of ideal speed at which 50% of the turns were positive or negative was determined by plotting the direction of the initial steering adjustment (binary coded so that negative adjustments were coded as zeros and positive adjustments were coded as ones) as a function of ideal speed at the onset of steering adjustments. We then estimated the critical value by fitting the data using following logistic function:

$$y = 1\Big/\left(1 + e^{-k(c-v)}\right) \quad (1)$$

where $v$ is the ideal speed, $c$ is the critical value of $v$ at which the transition from negative to positive turns occurs, and $k$ is a measure of the slope at point $c$ (see Peper et al. (1994) for a similar procedure).

# Results

## Measures of overall success

### *Percentage of successful trials*

To determine the overall success with which subjects were able to perform the task, we first calculated the percentage of trials in which subjects intercepted the target. The data from blocks 1–4 (in which maximum speed varied across

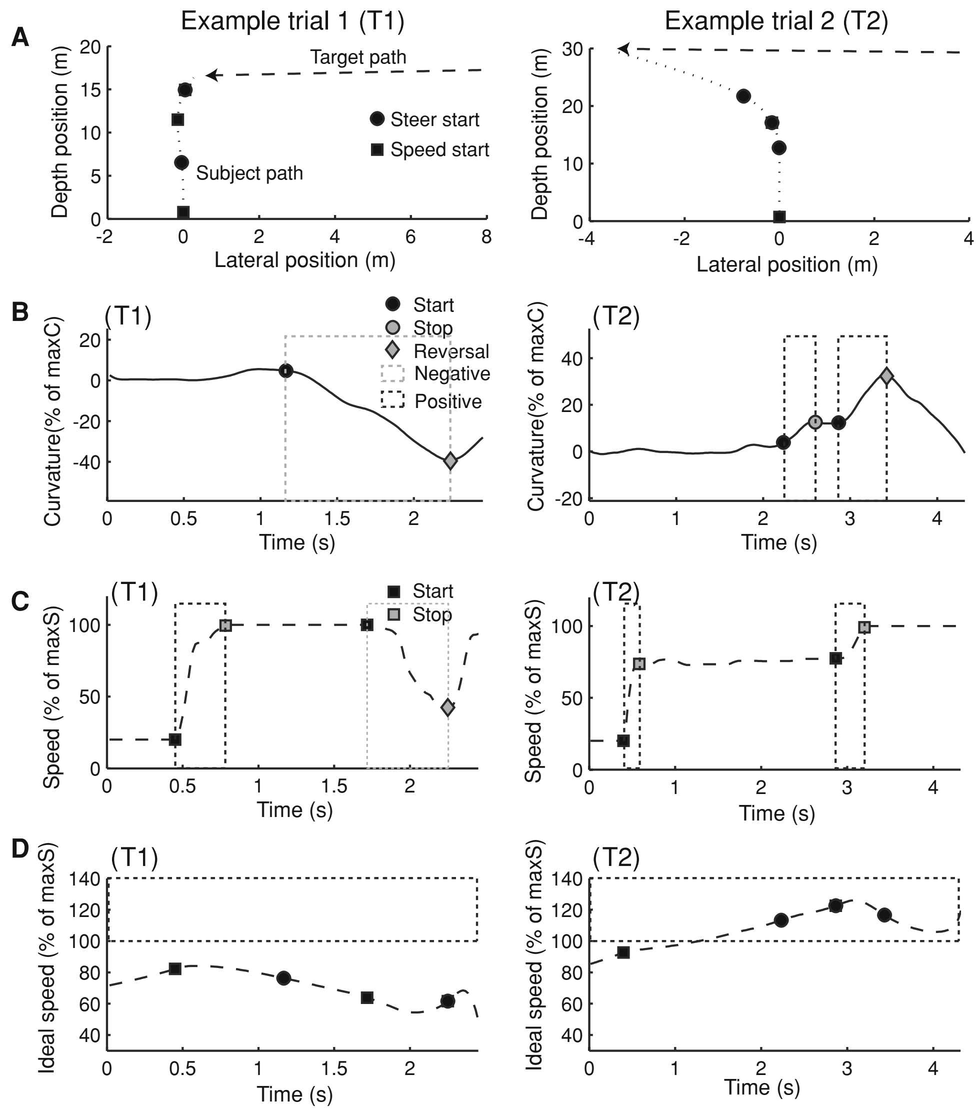


**Fig. 3** Exemplary trials representing subject and target path (**a**) and associated dependent variables (**c**–**d**). Curvature (**b**) and speed of travel (**c**) time series expressed as a percentage of maximal capabilities. Ideal speed expressed in intrinsic units was computed for each frame (**d**). Both positive and negative adjustments initiation (start or reversal) and end (stop or reversal) are marked in all four panels (only starts are represented in **a** and **d** for clarity

groups) and blocks 5–10 (in which maximum speed was the same across groups) were pooled for this analysis. For blocks 1–4, the percentage of successful trials was 89, 79.8, and 71.6% for the slow, medium, and fast groups. For blocks 5–10, the percentage of successful trials was 83.1, 82.7, and 85.8%.

The percentage of successful trials provides a good indication of overall success, but is a potentially unreliable measure for comparing performance across groups. Recall that trials were considered successful when the distance between the subject and the target was <0.5 m. As subject and target speed increase, the temporal precision needed to satisfy this criterion becomes more demanding. Thus, subjects in the fast group had to be more temporally precise than subjects in the slow group to intercept the target. In other words, the criterion used to determine whether or not the trial was successful favored the slow group. For this reason, final temporal error provides a more useful measure for comparing performance across groups.

*Final temporal error*

Two separate repeated measures ANOVA were conducted on the first four blocks and on the last six blocks using final temporal error as the dependent measure (see Fig. 4). In the first four blocks, neither the main effect of group ($F_{(2,27)} = 1.23$, $p = 0.29$) nor the main effect of block ($F_{(3,81)} = 0.73$, $p = 0.54$), nor the interaction ($F_{(6,81)} = 0.69$, $p = 0.65$) was statistically significant. Similarly, none of these effects were significant in the final six blocks. Thus, in terms of final temporal error, the manipulation of maximum speed did not affect performance.

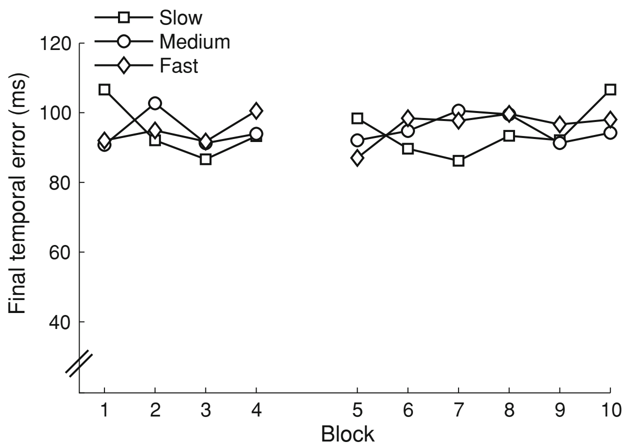


**Fig. 4** Mean final temporal error (ms) as a function of block, for all three groups

## Critical value of ideal speed at onset of steering adjustments

If subjects are sensitive to the limits of their speed capabilities, then they can intercept the target as quickly as possible by accelerating and turning toward the target when ideal speed is less than maximum speed, and turning ahead of the target when ideal speed is greater than maximum speed. Thus, the critical value of ideal speed at which 50% of the steering adjustments were positive (i.e., ahead of the target) should be close to 100% of maximum speed for all three groups. This would also mean that the critical value of ideal speed (in m/s) would be smaller for subjects in the slow group and larger for subjects in the fast group. Furthermore, if subjects completely recalibrated following the increase (slow group) or decrease (fast group) in maximum speed, then the critical value after the change (which occurred between blocks #4 and #5) should be close to 100% of the new maximum speed. Separate analyses were run for the initial steering adjustments and for subsequent steering adjustments that followed the initial adjustment on each trial.

### *Initial steering adjustments*

To obtain a more reliable estimate of the critical value, the data from blocks 1–4 and blocks 5–10 were pooled. The mean critical value of ideal speed (expressed in extrinsic units of m/s) at the onset of steering is shown in Fig. 5a.[5] During the first four blocks, the effect of group was significant ($F_{(2,24)} = 30.12$, $p < 0.01$), indicating that subjects in the slow and fast groups turned at smaller and larger values of ideal speed, respectively, compared to the medium group. Post hoc comparisons (Scheffe) showed that the mean extrinsic ideal speed was different across all three groups ($p < 0.01$). When ideal speed was expressed as a percentage of maximal speed (Fig. 5b), the critical value of ideal speed was not statistically different across groups ($F_{(2,24)} = 0.088$, ns), and close to 100% for all three groups. Thus, as expected, subjects in all three groups tended to turn in the direction of the target when ideal deceleration was less than maximum deceleration and ahead of the target when ideal deceleration was greater than maximum deceleration.

In the last six blocks, the ideal speed at the transition point did not significantly differ across groups ($F_{(2,23)} = 1.78$, ns), which indicates that subjects rapidly recalibrated to their new action capabilities.[6] If subjects had not recalibrated, the slow group would be expected to have a lower critical value and the fast group would have a larger critical value, as in the first four blocks.

### *Subsequent steering adjustments*

The same pattern of results was found for subsequent adjustments. A repeated measures ANOVA with blocks (1–4 vs. 5–10) and group as factors was performed on the critical value of ideal speed expressed both in extrinsic and in intrinsic units. When ideal speed was expressed in extrinsic units, the three groups differed from each other in the four-first blocks ($F_{(2,18)} = 55.490$, $p < 0.01$).[7] Post hoc (Scheffe) tests showed that the transition point corresponded to a lower (higher) value of ideal speed in the slow (fast) group compared to the ideal speed at the transition point of the medium group (Fig. 6a). In intrinsic units, ideal speed was not statistically different across groups regardless of the level of block (Fig. 6b).

## Ideal speed at onset of positive and negative steering adjustments

The preceding analysis revealed that subjects tended to make positive adjustments when ideal speed was greater than maximum speed and negative adjustments when ideal speed was less than maximum speed. However, analysis by itself does not tell us anything about how sensitive subjects were to the limits of their speed capabilities. If subjects knew their limits with good precision, then the mean value of ideal speed at the onset of positive adjustments should be close to 100%. The corresponding value for negative

[5] Data from five subjects were excluded because no reliable transition point was observable (e.g., these subjects always initially turned left).

[6] Data from four subjects were eliminated from this analysis for the same reason.

[7] Two subjects from the slow group, three from the medium group, and three from the fast group were eliminated from this analysis because there were too few curvature changes to calculate the transition point in one of the four blocks considered in this analysis.

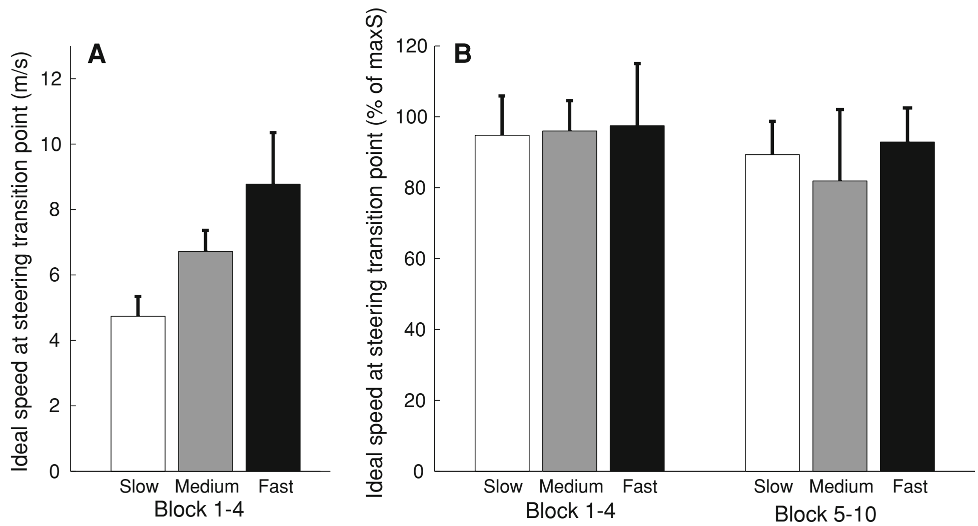


**Fig. 5** Mean ideal speed at the critical point at which the likelihood of turning left and right are equal, computed on the basis of the initial steering adjustments **a** in extrinsic units (m/s) and **b** in intrinsic units (percentage of maximum speed), as a function of block for all three groups (slow, medium, and fast group). *maxS* maximum speed

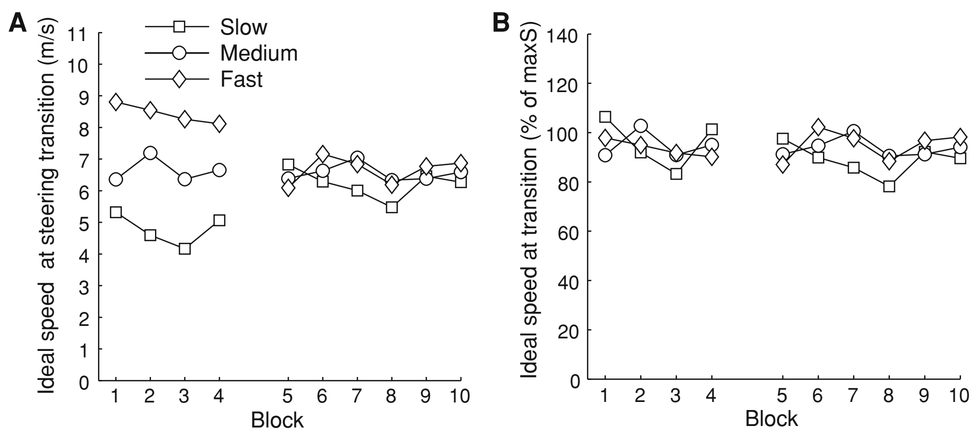


**Fig. 6** Mean critical value of ideal speed, computed on the basis of the subsequent steering adjustments **a** in extrinsic units (m/s) and **b** in intrinsic units (percentage of maximum speed), as a function of block for all three groups (slow, medium, and fast group). *maxS* maximum speed

adjustments should be <100% if subjects attempted to intercept the target as quickly as possible. Further, the mean values of ideal speed at the onset of positive (and negative) adjustments should be the same for all three groups, when ideal speed is in intrinsic units of maximum speed.

*Initial steering adjustment*

Figure 7 shows the mean value of ideal speed at the onset of positive (black bars) and negative (gray bars) initial steering adjustments for the data from blocks 1–4. The data are plotted in extrinsic units (m/s) in Fig. 7a and in intrinsic units (% of maximum speed) in Fig. 7b. When ideal speed was expressed in extrinsic units of m/s (Fig. 7a), the effect of group was significant for both positive adjustments ($F_{(2,28)} = 89.008,\ p < 0.01$),[8] and negative adjustments ($F_{(2,29)} = 353.777,\ p < 0.01$). In both cases, post hoc comparisons (Scheffe) showed that all three maximum speed conditions significantly ($p < 0.01$) differed from each other. When ideal speed was expressed as a percentage of maximum speed (Fig. 7b), the effect of group was not significant for both positive ($F_{(2,28)} = 0.833$, ns) and negative ($F_{(2,29)} = 0.899$, ns) adjustments. On average, positive adjustments were initiated when ideal speed was 94.8% of maximum speed, suggesting that subjects anticipated the need to turn ahead of the target shortly before ideal speed reached 100%. Negative adjustments were initiated when ideal speed was 82.4% of maximum speed. One might wonder why negative adjustments did not occur at lower values of ideal speed if subjects were attempting to intercept the target as quickly as possible. The answer is that the initial conditions did not allow it. Ideal speed at the beginning of the trial ranged from 58.3 to 100% (see Footnote 2), and increased rapidly until subjects accelerated. A more in-depth analysis revealed that subjects did initiate negative adjustments at lower values when the initial conditions allowed. At the slowest initial speed, mean ideal speed at the onset of negative adjustments was 66.5, 68.0, and 67.9% of

[8] Data from one subject were eliminated in this analysis, because there were no positive adjustments at the onset of steering (i.e., this subjects adopted a strategy consisting of always turning toward the right, initially).

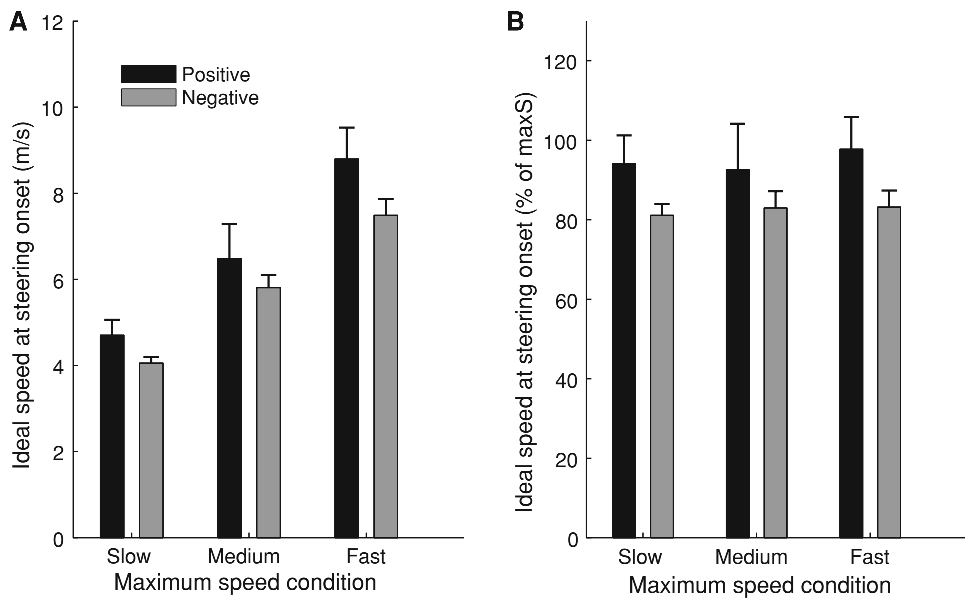


**Fig. 7** Mean ideal speed at the onset of left (positive) and right (negative) initial steering adjustments **a** in extrinsic units (m/s) and **b** in intrinsic units (% maximum speed) for all three groups (slow, medium, and fast group). *maxS* maximum speed

maximum speed in the slow, medium, and fast groups, respectively. We also grouped the last six blocks to test whether the change in maximum speed affected the ideal speed at steering onset. The analysis showed that there was no effect of group for positive ($F_{(2,29)} = 0.618$, ns) and negative ($F_{(2,29)} = 2.84$, ns) adjustments, providing additional evidence that subjects rapidly recalibrated to the new maximum speed during these blocks.

*Subsequent steering adjustments*

The results obtained for subsequent steering adjustments corresponding to grouped data of blocks 1–4 (Fig. 8) closely matched those obtained for the initial adjustments. In extrinsic units, ideal speed was significantly different across groups for both positive and negative adjustments ($F_{(2,29)} = 205.89, p < 0.01$ and $F_{(2,29)} = 381.28, p < 0.01$). When ideal speed was expressed in intrinsic units, however, the difference was not statistically significant ($F_{(2,29)} = 1.017$ and $F_{(2,29)} = 0.583$, respectively for positive and negative adjustments). Similarly, the analysis conducted in the last six blocks revealed no significant difference among all three groups for both positive ($F_{(2,29)} = 0.093$) and negative adjustments ($F_{(2,29)} = 1.45$).

What do these findings tell us about the coordination of steering and speed during interception? First, the fact that the mean ideal speed when subjects made positive adjustments was slightly <100% in all three conditions provides compelling evidence that subjects were sensitive to the limits of their speed capabilities. That is, they knew when it was no longer possible to intercept the target by only changing speed, and anticipated the need to turn ahead of the target. Such behavior is nicely illustrated in the sample trial in the right column of Fig. 3. At the beginning of the trial, ideal speed is greater than 80% of maximum speed and increasing. Within 500 ms, the subject increases speed to about 70% of maximum. Because this is slightly less than the speed needed to intercept, ideal speed continues to increase above 100%. Shortly after 2 s, the subject (almost simultaneously) turns ahead of the target and increases speed to 100% of maximum. This combination of positive steering and speed adjustments resulted in a gradual decrease in ideal speed toward 100%, and a successful interception at maximum speed.

Second, the fact that ideal speed when subjects made negative adjustments was considerably less than the corresponding value for positive adjustments is consistent with the expectation that steering would be controlled in a way that would allow subjects to intercept the target as quickly as possible. In the sample trial in the left column of Fig. 3, for example, ideal speed is initially around 70% of maximum speed and gradually increasing. The subject first increases speed to 100% of maximum, and later turns toward the target. Had the subject not intended to intercept the target as quickly as possible, one would have expected him or her to increase speed to <100% and turn ahead of the target. Such behavior might be expected in certain real-world situations, especially those in which there is no advantage to intercepting the target quickly and significant costs associated with moving at higher speeds. Subjects in our experiment, like defenders in football, controlled steering as if they intended to intercept the target while moving as quickly as possible.

Third, none of the preceding analyses revealed any effects of the change in speed capabilities, suggesting that recalibration occurred rapidly. To further investigate the

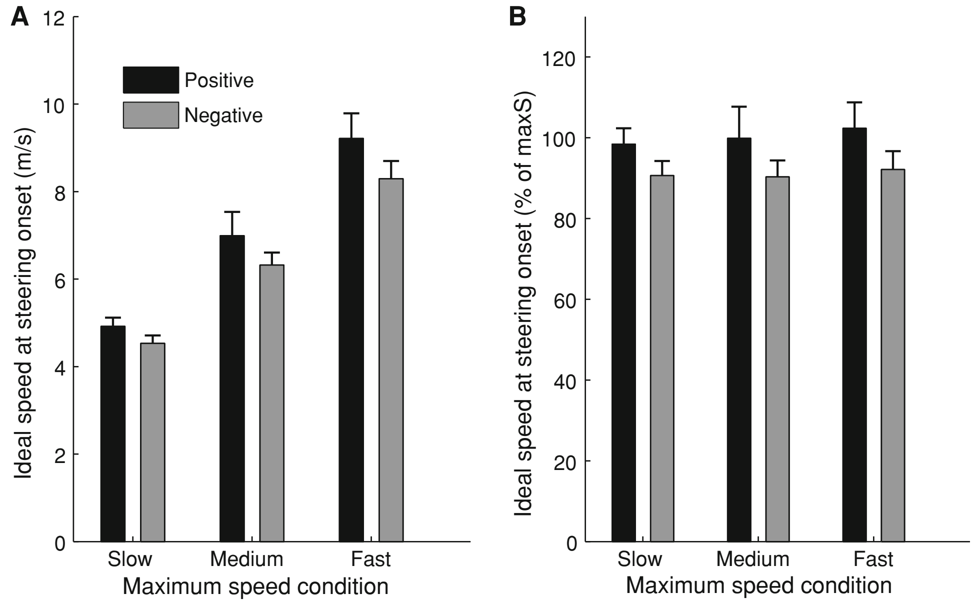


**Fig. 8** Mean ideal speed at the onset of positive and negative subsequent steering adjustments **a** in extrinsic units (m/s) and **b** in intrinsic units (% maximum speed) for all three groups (slow, medium, and fast group). *maxS* maximum speed

rate of recalibration, we compared the averaged scaled ideal speed at the onset of initial steering adjustments in blocks 4 and 5 for all three groups. Had subjects not recalibrated to the change in speed capabilities, we would expect the slow group to initiate adjustments at higher values of ideal speed, whereas the reverse pattern would be expected for the fast group. However, no significant differences between blocks 4 and 5 were found for both positive ($F_{(1,25)} = 1.17$, ns) and negative ($F_{(1,25)} = 1.738$, ns) adjustments, suggesting that complete recalibration occurred within the 20 trials of block 5.

Given the rapid rate at which recalibration occurred, we looked for evidence of recalibration at the individual trial level by comparing the first five trials of block 5 to the average of block 4. To obtain a sufficiently reliable estimate of ideal speed at onset at the individual trial level, it was necessary to combine initial and subsequent adjustments (both positive and negative). This analysis revealed a significant group × trial interaction ($F_{(10,130)} = 3.89$, $p < 0.01$; see Fig. 9). Post hoc testing (Scheffé) confirmed that the slow and fast groups significantly differed only in the first two trials of block 5 (75.5 and 80.7% for the slow group vs. 103.9% and 98.1% for the fast group), as would be expected if participants had not yet completely recalibrated. Overall, the findings suggest that the sudden change in speed capabilities affected behavior, but that complete recalibration was achieved within a small number of trials.

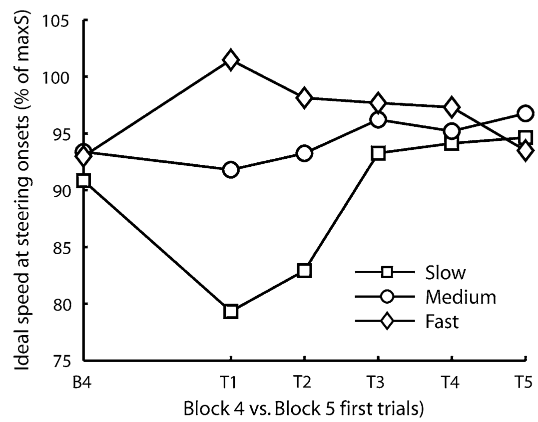


**Fig. 9** Mean ideal speed at the onset of steering adjustments in block 4 and the first five trials of block 5

### Ideal speed at onset of positive and negative speed adjustments

All of the preceding analyses focused on steering adjustments. In the remainder of the "Results" section, we present analyses of speed adjustments. First, we calculated the ideal speed at the onset of initial and subsequent speed adjustments. Again, the data were pooled according to blocks (1–4 and 5–10). Positive adjustments corresponded to increases in speed and negative adjustments corresponded to decreases in speed. All initial speed adjustments were positive, but subsequent speed adjustments could be either positive or negative.

#### *Initial speed adjustments*

The pattern of results that was found for ideal speed at the onset of initial speed adjustments was similar to that found for steering adjustments. Subjects in the slow and fast groups initiated speed adjustments at lower and higher values of ideal speed, respectively, compared to the medium group, $F_{(2,29)} = 2080.8$ (see Fig. 10a). Post hoc

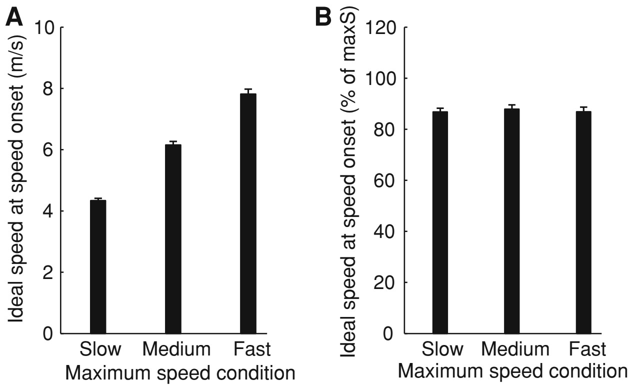


**Fig. 10** Mean ideal speed at onset of initial speed adjustment **a** in extrinsic and **b** in intrinsic units, for all three groups. *maxS* maximum speed

comparison (Scheffe) confirmed that these differences were significant at the $p < 0.01$ level. When ideal speed was expressed as a percentage of maximum speed (Fig. 10b), this effect was no longer significant ($F_{(2,29)} = 1.424$). In the last six blocks, there was no significant effect of group ($F_{(2,29)} = 1.052$).

*Subsequent speed adjustments*

Data were collapsed for blocks 1 to 4 and blocks 5 to 10 to run statistical analyses. In the first four blocks, when ideal speed was expressed in extrinsic units (Fig. 11a), there was a significant effect of group on both positive ($F_{(2,29)} = 144.84$, $p < 0.01$) and negative ($F_{(2,28)} = 85.303$, $p < 0.01$)[9] adjustments. Post hoc comparisons confirmed that all three groups significantly differed from each other (Scheffé). In contrast, when ideal speed was expressed in intrinsic units (Fig. 11b), there was no significant difference between groups, neither for the positive adjustments ($F = 2.816$), nor for the negative adjustments ($F = 1.096$). Similarly, in the last six blocks, there was no significant difference across groups, for both positive ($F_{(2,29)} = 0.616$) and negative adjustments ($F_{(2,28)} = 0.114$, ns).

Subject speed at the onset of steering

The analyses of steering adjustments revealed that subjects turned toward the target when ideal speed was less than ~85% of maximum speed and ahead of the target when ideal speed was greater than ~95% of maximum speed. We interpret this finding as a reflection of actors' sensitivity to the limits of their action capabilities—that is, they can reliably perceive whether or not it is possible to intercept the target within the limits of their speed capabilities. However, further analyses are necessary to rule out an alternative explanation that does not require actors to know their speed limitations. If subjects accelerated to maximum speed before initiating the steering adjustment, then they could have relied on the change in bearing angle to tell them which way to turn. Recall that the change in bearing angle specifies the sufficiency of the actor's current velocity. Thus, if the bearing angle is decreasing while the actor is moving at maximum speed, this indicates that the actor's current speed (which in this case is his or her maximum speed) is insufficient to intercept the target without changing directions. The only way to intercept the target is to turn ahead of the target. In other words, although the change in bearing angle does not, in general, provide information about whether or not the target can be intercepted, it does when the actor is moving at his or her maximum speed. Hence, if subjects in the present experiment made their initial steering adjustments only after reaching maximum speed (as in the sample trial in the left column of Fig. 3), then the findings can be explained without reference to sensitivity to action limits. On the other hand, if initial steering adjustments were made before reaching maximum speed (as in the sample trial on the right column of Fig. 3), then subjects must have known their action limits.

We calculated the percentage of initial steering adjustments that occurred prior to reaching 90% of maximum speed. In the fast condition, 1,249 out of 1,908 initial steering adjustments (65.4%) were executed prior to the point at which current speed reached 90% of maximum speed. Similarly, in the medium condition, 1,433 out of 1,863 (76.9%) of the initial steering adjustments were executed before current speed reached 90% of maximum speed. Finally, in the slow group, 1,339 out of 1,768 (75.7%) initial steering adjustments were executed before current speed reached 90% of maximum speed. Further analyses revealed that speed adjustments were initiated before steering adjustments on just 59.5% of trials in which the initial steering adjustment was positive and 53.5% of trials in which the initial steering adjustment was negative. These results clearly rule out an explanation based on a constant bearing angle strategy and confirm that subjects relied on their sensitivity to the limits of their speed capabilities to perceive whether or not the target could be intercepted.

Maximum and final speed

Recall that the analyses of steering adjustments suggested that subjects controlled steering in a way that would allow them to intercept the target as quickly as possible (i.e., by moving at or near 100% of maximum speed). To verify this, we first calculated the percentage of trials in which

[9] Data from 1 participant in the fast condition was excluded because no subsequent negative speed adjustments were recorded.

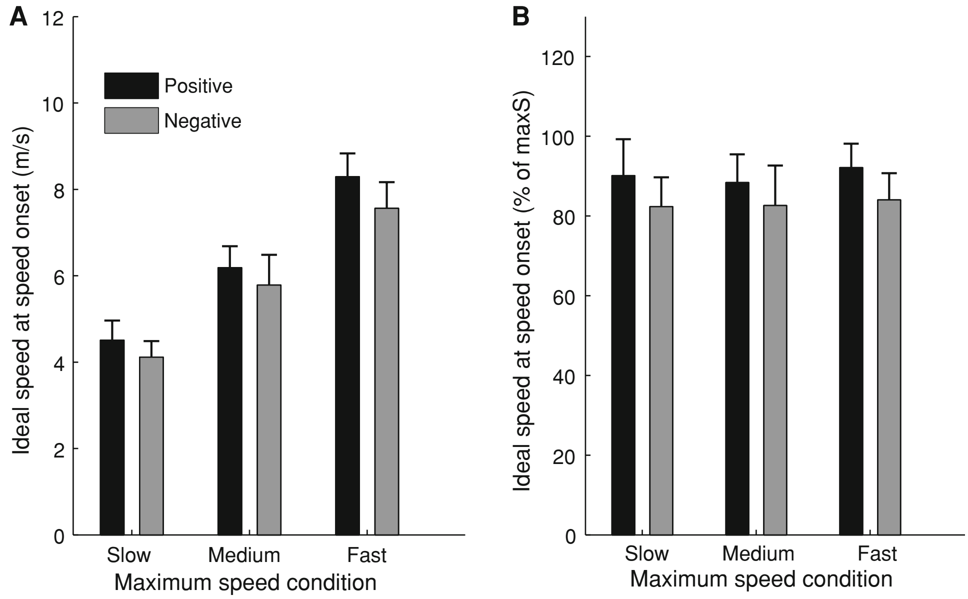


**Fig. 11** Ideal speed at onset of subsequent speed adjustments in extrinsic units (**a**) and intrinsic units (**b**) for positive and negative speed adjustments, for all three groups in the first four blocks. *maxS* maximum speed

subjects exceeded 95% of maximum speed at some point during the approach. In the first four blocks, subjects exceeded 95% of maximum speed on 86.4% (slow), 92.1% (medium), and 89.8% (fast) of trials. In the last six blocks, subjects exceeded 95% of maximum speed on 83.6% (slow), 84.8% (medium), and 88.2% (fast) of the trials. We also calculated the mean speed at the moment of interception. In blocks 1 through 4, subjects were traveling at 90.3% (slow), 94.0% (medium), and 93.4% (fast) of maximum speed. In blocks 5 through 10, subjects in the slow, medium, and fast groups were traveling at 89.4, 91.9, and 91.9% of maximum speed, respectively. Thus, as expected, subjects tended to accelerate to near maximum speed, and intercept the target while traveling as quickly as possible.

## Discussion

The primary aim of this study was to extend previous investigations of locomotor interception to situations in which actors can control both steering and speed. More specifically, we tested the hypothesis that steering and speed are coordinated in such a way that the speed required to intercept the target (i.e., the ideal speed) is kept below maximum speed. When ideal speed is less than maximum speed, the actor can intercept the target by continuing to move in the same direction and adjusting speed, or by turning toward the target. Turning toward the target requires actors to move at speeds that are higher than those required if current heading is maintained, but also allows them to intercept the target more quickly. Because there was no cost (e.g., in terms of effort) to moving quickly through the simulated environment used in our experiment, we expected subjects to accelerate and turn toward the target when ideal speed was less than maximum speed. This allowed them to intercept the target as quickly as possible, as is commonly the goal in sports-related tasks. When ideal speed is greater than maximum speed, the actor cannot intercept the target without turning in the same direction that the target is moving. Thus, we expected that subjects would turn ahead of the target when ideal speed exceeded maximum speed.

As predicted, we found that subjects tended to turn ahead of the target slightly before ideal speed reached 100% of maximum speed, and toward the target when ideal speed was 80 to 90% of maximum speed. In both cases, subjects generally accelerated to intercept the target as quickly as possible. Further, when maximum speed was manipulated between groups, the critical value of ideal speed at which subjects turned toward (or ahead) of the target 50% of the time was smaller for slower subjects and greater for faster subjects. However, the ratio of the critical value of ideal speed maximum speed was close to 100% of maximum speed for all three groups. Finally, when maximum speed suddenly increased or decreased, subjects rapidly recalibrated by turning at larger or smaller values of ideal speed.

### Implications for models of locomotor interception

The present findings pose a challenge for existing models of interception, such as the CBA and RV models. To reiterate, these models make no predictions about how speed and steering are coordinated during interception. Further, these models ignore the fact that there are limits to how fast actors can move and turn, and that actors must behave in ways that take these limits into account. This is because the optical variables in such models (e.g., the change in bearing angle in the CBA model) specify the sufficiency of the actors' current velocity. The only situation in which such variables tell actors whether or not the target can be intercepted is when they are moving at their maximum speed. Thus, when actors relying on the change in bearing angle are moving at less than maximum speed, they cannot reliably perceive whether or not the target can be intercepted within the limits of their speed capabilities. In our experiment, subjects made steering adjustments in the appropriate direction before reaching maximum speed. In other words, they coordinated steering and speed in a way that cannot be explained on the basis of prospective control models.

On the other hand, the results of the present study are consistent with the hypothesis that actors are sensitive to the limits of their speed capabilities, and that such sensitivity serves as a constraint on the coordination of steering and speed during interception. Thus, actors adjust steering so that the speed required to intercept the target is less than their maximum speed; that is, so that it is within their capabilities to intercept the target without making any further steering adjustments. This strategy is very much in the spirit of Gibson's (1986) theory of affordances, which emphasizes the importance of knowing boundaries that separate possible from impossible actions. As such, Fajen (2007a) used the term *affordance-based* control to refer to the strategies in which actors make adjustments so that the intended action is always possible within the limits of their action capabilities. Up to this point, empirical support for affordance-based control has come from studies of visually guided braking (Fajen, 2005a, c, 2007b). Thus, the present study helps to illustrate that the same principle can be applied more generally to other visually guided actions.

The ability to take one's speed capabilities into account constrains the way in which speed and direction are coordinated, but does not reduce the space of possible states to a single desired speed and direction. There is still an infinite number of combinations of speed and direction that allow one to intercept the target within the limits of one's speed capabilities. The advantage of this approach is that it allows for flexibility where it is needed to intercept the target in different ways (e.g., to achieve a soft or hard collision), but does not allow variability where it is not tolerated. [This is not unlike the way in which variability within the motor system is distributed when performing multi-degree of freedom motor tasks (Latash et al. 2007)].

Furthermore, although the focus of this study was on speed capabilities, there are other limitations of the visual and motor systems that also must be taken into account during any visuo-motor task. The presence of perceptual noise and motor variability introduces a significant source of error that must be taken into account during the execution of movements. In studies of reaching, people adjust their aim point to optimally compensate for the costs associated with errors in reaching which was introduced by motor variability (Trommershäuser et al. 2005). When people perform closed-loop visually guided actions, they adapt their control strategy to different kinds of signal-dependent noise, making small adjustments when noise is proportional to controller input and large adjustments when noise is inversely proportional (Chhabra and Jacobs 2006). In addition to motor variability, inherent neural delays and neuromuscular lags limit the speed with which visual information can be used to adjust movement, and also must be taken into account (see Zago et al. (2009) for a review of this topic as it relates to interception).

A challenge for future research is to better understand how all of these factors are taken into account during locomotor interception. The framework that is arguably best suited for building models of perceptual-motor tasks that require satisfying multiple task goals is optimal feedback control (Todorov and Jordan 2002; Todorov 2004). Such models are useful for generating predictions about behavior that arises from adopting control strategies that are optimized for composite cost functions (e.g., Liu and Todorov 2007). However, using these tools to build models of tasks that are characterized by a tight coupling of information in optic flow and locomotion would be a new direction and would require significant developments.

### *Implications for models of projectile interception*

Although our focus was on the interception of targets moving parallel to the ground plane, similar issues arise in the context of projectile interception (e.g., running to catch a fly ball). When a fly ball is hit directly toward a fielder, running forward or backward such that the elevation angle of the ball increases but does not reach 90° will lead the fielder to the landing location in time to catch the ball (McLeod and Dienes 1996). More often than not, however, fly balls are hit off to the side, and therefore require the fielder to also move laterally into the plane of the ball's flight. This component of the problem is similar to the problem of intercepting a target moving parallel to the ground plane. Not surprisingly, keeping the ball at a constant bearing angle has been proposed as a strategy used by fielders to control the lateral component of their movement (Chapman 1968). A variant of this model is to null the acceleration of the bearing angle (McLeod et al. 2006). The latter model allows for the variability that is observed in the speed with which fielders move into the plane of the ball (e.g., catching the ball while still on the run versus running ahead of the ball and then slowing down). If the conclusions of the present study also apply to projectile interception, then fielders' sensitivity to their locomotor capabilities should be considered as a possible constraint on the manner in which they move laterally into the plane of the ball's flight path.

### Information and calibration

Recall that ideal speed corresponds to the speed that, if maintained, will result in a successful interception without making any further changes to speed or direction. In terms of spatial variables, ideal speed is equal to the distance along the locomotor axis from the actor to the point at which the target will intersect the locomotor axis divided by the amount of time before the target reaches the locomotor axis (see Fig. 1). In principle, ideal speed could be perceived on the basis of information about passing distance, time-to-passage, and current speed. Passing distance (PD) corresponds to the distance along the locomotor axis between the actor and the target at the moment that the target intersects the locomotor axis, and is optically specified in units of target size by the following equation:

$$\frac{\mathrm{PD}}{2R} \approx \frac{\dot{\beta}}{\dot{\theta}} \tag{2}$$

where $R$ is the radius of the target, $\dot{\beta}$ is the rate of change of the bearing angle $\beta$, and $\dot{\theta}$ is the rate of optical expansion of the target (Bootsma 1991; Regan and Kaushal 1994). Time-to-passage (TTP) is the amount of time before the target crosses the locomotor axis, and is optically specified by:

$$\mathrm{TTP} \approx \frac{\theta}{\dot{\theta}} - \frac{\beta}{\dot{\beta}} \tag{3}$$

(Bootsma and Oudejans 1993). The ratio of these two variables specifies the change in speed required to intercept the target; that is, the difference between the ideal speed and the current speed. Current speed is optically specified by global optic flow rate (GOFR). Loosely speaking, GOFR corresponds to the rate of optic flow of ground texture elements under a moving observer, which is proportional to speed as long as eyeheight is constant.[10] Thus, ideal speed is optically specified by:

$$\left(\frac{\left(\frac{\dot{\beta}}{\dot{\theta}}\right)}{\left(\frac{\theta}{\dot{\theta}} - \frac{\beta}{\dot{\beta}}\right)}\right) - \mathrm{GOFR} \tag{4}$$

For such information to be useful for guiding interception in a manner suggested by the affordance-based control model, it must be calibrated in units of maximum speed. We believe that calibration is best understood as an ongoing process in which information about ideal speed is continually rescaled. Following Jacobs and Michaels (2006), we can represent the scaling factor as a parameter $k$ such that perceived ideal speed is characterized by:

$$k \times \left(\left(\frac{\left(\frac{\dot{\beta}}{\dot{\theta}}\right)}{\left(\frac{\theta}{\dot{\theta}} - \frac{\beta}{\dot{\beta}}\right)}\right) - \mathrm{GOFR}\right) \tag{5}$$

Note that for some value of $k$, Eq. 5 specifies ideal speed in units of maximum speed. In other words, when information about ideal speed is properly calibrated, it tells the actor about the percentage of maximum speed that is necessary to intercept the target without changing direction. Thus, like subjects in the present experiment, actors who are properly calibrated can directly perceive when it is possible to intercept the target by turning toward it, and when it is necessary to turn ahead of the target.

### Limitations of the present study

Subjects in the present study coordinated steering and speed in such a way that allowed them to intercept the target as quickly as possible. Such behavior is probably a reflection of the instructions to intercept the target quickly, as well as subjects' desire to complete the experimental session more quickly, and the fact that there was no additional cost in terms of effort associated with traveling through the simulated environment at higher speeds. Of course, in the real world, factors, such as fatigue and traction can constrain the ways in which actors change speeds and directions. This may affect the critical value of ideal speed at which actors start to turn ahead of the target, but will not affect the overall strategy. For example, consider the situation in which ideal speed is 50% of maximum speed. Subjects in our experiment tended to accelerate to maximum speed as they turned toward the target. If, however, changing direction of locomotion is risky due to poor traction (e.g., on a muddy playing field), then the actor might intercept the target by continuing to move in the same direction at 50% of maximum speed. Even if traction is excellent, actors in the real world may try to conserve energy by turning ahead of, rather than toward, the target. This will increase the time it takes to intercept the target, but will also allow the actor to move at a slower speed.

[10] More specifically, GOFR is equal to $v/e$, where $v$ is observer speed and $e$ is eyeheight. When an observer moves parallel to a textured ground plane, the optical velocity of texture elements on the ground varies with the Azimuth and declination of the element. In addition, GOFR acts as a global multiplier that affects the optical motion of all points in the same way. For situations in which eyeheight is fixed, GOFR is proportional to speed. See Larish and Flach (1990) and Warren (1982) for more details.

Such factors are difficult to investigate in a simulated environment. Future studies in which these factors are manipulated in the real world are needed. Thus, the present study can be thought of as a first step toward understanding how steering and speed are coordinated during interception. The affordance-based approach adopted in this paper provides a natural framework for future investigations of this topic.

**Acknowledgments** Brett R. Fajen was supported by grants from the National Science Foundation (BCS 0236734 and BCS 0545141). We thank Mark Stenpeck for programming the simulation.

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