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Affordance-based versus current-future accounts of choosing whether to pursue or abandon the chase of a moving target

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Affordance-based control and current-future control offer competing theoretical accounts of the visual control of locomotion. The aim of this study was to test predictions derived from these accounts about the necessity of self-motion (Experiment 1) and target-ground contact (Experiment 2) in perceiving whether a moving target can be intercepted before it reaches an escape zone. We designed a novel interception task wherein the ability to perceive target catchability before initiating movement was advantageous. Subjects pursued a target moving through a field in a virtual environment and attempted to intercept the target before it escaped into a forest. Targets were catchable on some trials but not others. If subjects perceived that they could not reach the target, they were instructed to immediately give up by pressing a button. After each trial, subjects received a point reward that incentivized them to pursue only those targets that were catchable. On the majority of trials, subjects either pursued and successfully intercepted the target or chose not to pursue at all, demonstrating that humans are sensitive to catchability while stationary. Performance also degraded when the target was floating rather than in contact with the ground. Both findings are incompatible with the current-future account and support the affordance-based account of choosing whether to pursue moving targets.

Introduction

An important but neglected aspect of interception on foot is perceiving when a target is catchable and worth the effort of pursuing. Oftentimes, targets move too quickly to catch; even for catchable targets, the costs of pursuit sometimes outweigh the benefits of catching. For example, on the ball field, outfielders must perceive when catching a fly ball in the air is not possible, and instead run to where the ball will be after it bounces. Likewise, in the wild, chasing after prey that are moving too fast to catch wastes valuable energy. An analogous problem arises in other contexts, including those that do not involve interception. For example, drivers must perceive when they cannot brake fast enough to avoid a collision, so they may swerve around the obstacle (Fajen, 2005). The common thread that ties these problems together is the concept of possibilities for action, or what Gibson (1979) referred to as *affordances*. Although the perception and selection of affordances are critical to many visual locomotor control tasks, their role in such tasks is often overlooked (Fajen, 2007).

In contrast, there is a great deal of research on the realization of affordances, which involves the ongoing regulation of movement based on perceptual information. In accordance with the principles of information-based control (Warren, 1998; Zhao & Warren, 2015), it is generally understood that online visual guidance in these types of tasks emerges from the coupling of currently available information (e.g., in optic flow fields) and action as captured by some law of control (Bootsma, Ledouit, Casanova, & Zaal, 2016; Chapman, 1968; Gibson, 1958; Lee, 1976; Warren, 1988). According to some information-based accounts, the informational variables on which actors rely specify what will happen if current conditions persist: whether running at the current speed will result in interception,

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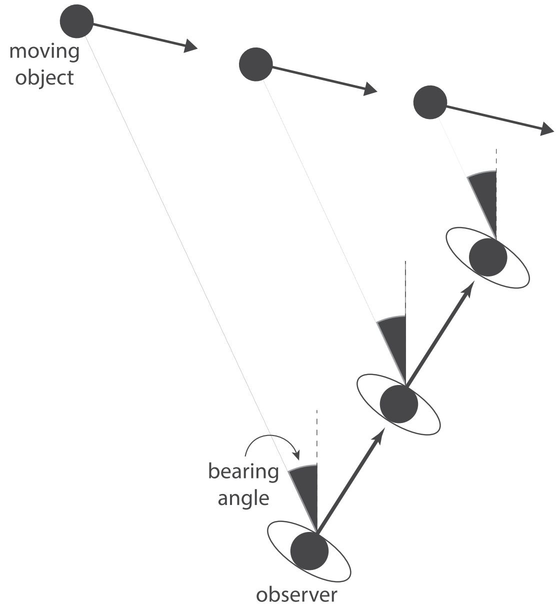

Figure 1. The CBA strategy of interception. The bearing angle (black wedge) is the optical angle between the target and a fixed reference direction. Reprinted from Fajen, 2013.

or whether the current rate of deceleration will result in a collision with an oncoming wall. Bootsma (2009) coined the term “current future” to describe such models. From this perspective, control is about altering the current future to match the desired one.

Although current-future models were originally developed to account for online visual guidance, it has been suggested that the same information could also be used to perceive affordances for locomotor control tasks (Oudejans, Michaels, Bakker, & Dolné, 1996). In the next section, we explain how current-future information could provide a basis for distinguishing between possible and impossible actions.

Perception of catchability from the current-future perspective

Currently, the predominant model of online visual guidance during locomotor interception in humans is the constant bearing angle (CBA) strategy (Chardenon, Montagne, Buekers, & Laurent, 2002; Fajen & Warren, 2004; Fajen & Warren, 2007; Zhao & Warren, 2017). The bearing angle is the optical angle between the target and some reference direction that is fixed in exocentric coordinates (see Figure 1). If the bearing angle remains constant while the actor is moving, the target is on a collision course with the actor, and interception will be successful assuming current conditions persist. The CBA strategy is thus to move in such a way as to null the rate of change of the bearing angle as the chase evolves. This model is parsimonious, well established, and yields predictions of locomotor trajectories that closely match those exhibited in psychophysical experiments (Fajen & Warren, 2007).

The CBA model epitomizes the current-future account of online visual guidance because the change in bearing angle specifies what will happen in the future if current conditions persist (i.e., the actor’s current future). Oudejans et al. (1996) proposed that current-future information, in addition to serving as a basis for visual guidance, could also specify catchability. They developed this account in the context of the so-called outfielder problem, but the same logic could also be applied to explain the perception of catchability of targets that move along the ground. If the actor is moving in such a way that the change in bearing angle is zero, the actor’s current speed and direction are sufficient to intercept the target. As such, the target is catchable as long as current speed can be maintained. If the actor is moving as quickly as possible and the bearing angle is shrinking, the actor’s current speed (which is also his or her maximum speed) is insufficient. Hence the target is uncatchable (at least, if the actor is restricted to moving in the current direction).

This account demonstrates that current-future information could be used to perceive catchability, and therefore determine whether to continue to pursue a moving target. Nevertheless, the current-future account of perceiving catchability is limited in that it does not explain common aspects of behavior that are crucial to the survival of many organisms. The change in bearing angle only specifies which of three states the actor could currently be in: on course to pass in front, on course to intercept, or on course to pass behind. As such, when an actor is stationary, the change in bearing angle only specifies that the actor is on course to pass behind the target. It does not specify if it is within the actor’s capabilities to catch the target; that is, if the target is catchable. Even after movement is initiated, a shrinking bearing angle tells the actor only that the current speed is insufficient to intercept the target; it does not tell the actor whether the target is catchable if running speed was further increased. As explained earlier, for a shrinking bearing angle to specify that a target is uncatchable, the actor would have to be moving at maximum speed. For example, a soccer player would need to run at a full sprint to perceive whether the ball can be reached before it goes out of bounds. Likewise, a predator would have to chase its prey at full speed before perceiving that the prey cannot be caught.

The prediction of the current-future account that an actor must move at maximum speed (or even at all) to perceive catchability is inconsistent with the findings from Fajen, Diaz, and Cramer (2011), who examined catchability judgements of fly balls when subjects were moving versus when they were standing still. Subjects in that study were tasked with catching fly balls in a virtual environment, but on some trials the ball disappeared, and they instead made judgements about whether they would have caught the ball if it had remained visible. In

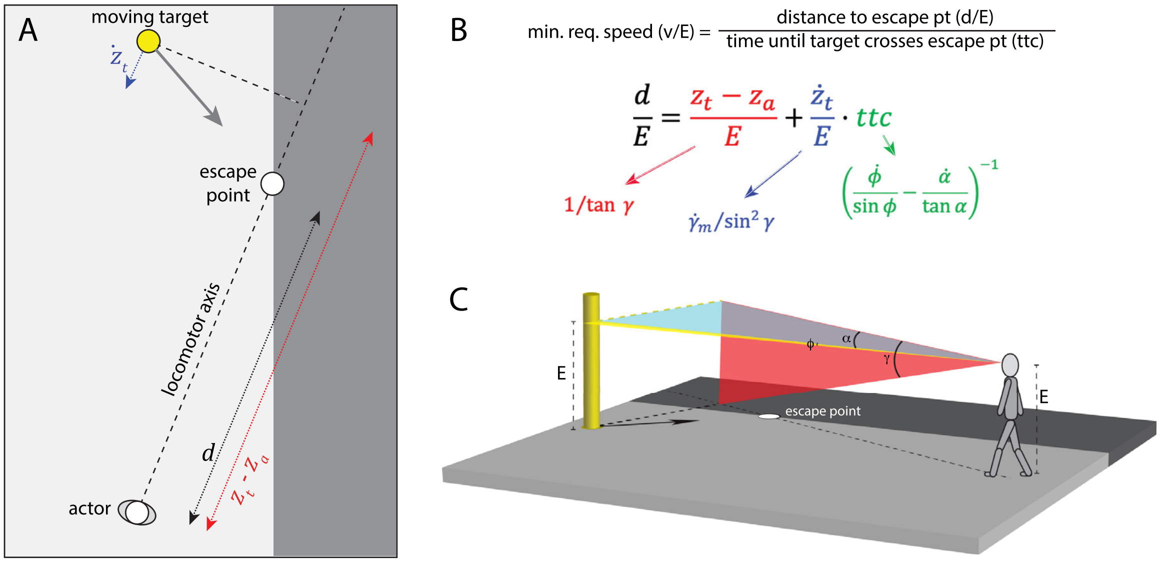

Figure 2. (A) Top-down view of scenario in which an actor is attempting to catch a moving target (yellow circle) before it escapes into a “safe zone” (dark gray region). z_t and z_a are the positions along the locomotor axis of the moving target and actor, respectively, and $\dot{z}_t$ is the speed of the target along the locomotor axis. d is the distance from the actor to the escape point (white circle). (B) Minimum required locomotor speed in units of eye height (E) can be expressed as a ratio of distance to time, which in turn can be expressed in terms of the following optical variables and their rates of change: the optical angle (γ) between the target-ground contact and the point on the target at the actor’s eye height (i.e., angular declination), the lateral optical angle formed by the leading edge of the target and the locomotor axis (α), and the optical angle of the edges of the target (ϕ). The subscript m under $\dot{\gamma}$ indicates the component of $\dot{\gamma}$ owing to the motion of the target independent of the actor’s self-motion. (C) Illustration of optical variables used in B. Adapted from Fajen, 2013.

one condition, subjects made this judgment based on what they saw before movement was initiated. Fajen et al. found that subjects’ judgments were no more accurate when moving than when standing still.[1]

More recent work investigating the interception of fly balls casts further doubt onto the current-future account (Postma, Lemmink, & Zaal, 2018; Postma, Otter, & Zaal, 2014; Postma, Smith, Pepping, van Andel, & Zaal, 2017). Postma et al. (2017) found that at the moment that subjects reported fly balls as uncatchable, they were running at less than half of their maximum speed with negligible acceleration. Such responses are inconsistent with any current-future account of perceiving catchability, including one based on the fly ball’s optical acceleration, the dominant model for interception of a fly ball (Chapman, 1968; Fink, Foo, & Warren, 2009; Michaels & Oudejans, 1992), and are better explained from an affordance-based perspective (Postma et al., 2018).

Perception of catchability from the affordance-based perspective

The affordance-based account holds that humans are sensitive to their potential actions, or affordances, which are partly defined by the actor’s body size and action capabilities (Fajen, 2013; Fajen, Riley, & Turvey, 2008; Gibson, 1979; Turvey, 1992). For the task of interception, the affordance is defined by the speed needed to intercept the target in relation to the actor’s ability to move (i.e., how catchable the target is).

The affordance-based strategy for perceiving catchability and guiding locomotion to intercept a moving target utilizes a composite optical variable that specifies the speed required for interception (Fajen, 2013). For the purposes of the present study, it is sufficient to understand the following three points. First, the detection of this information allows for the perception of the minimum required locomotor speed—in units of eye height (E)—at which the actor would need to move to ensure a collision by moving in a particular direction. To illustrate, let us assume that the actor is attempting to intercept the target before it escapes into a “safe zone” where it cannot be caught (see Figure 2A), and that it is moving (or intends to move) in the direction of the escape point.[2] The minimum speed required to intercept the target before it reaches the escape point is the quotient of the distance from the observer to the escape point (d) and the time remaining until the target crosses the locomotor axis (time-to-crossing or *ttc*; see Figure 2B). The numerator (d/E) can be expressed as a function of the position (z_a) of the actor, the position (z_t) and approach speed ($\dot{z}_t$) of the target along the locomotor axis, and the time-to-crossing. Furthermore, each of these quantities are themselves functions of the optical angles α, φ, and γ and their rates of change (see Figures 2B and C; see Fajen, 2013 for derivation).

Second, because one's eye height and one's maximum locomotor speed (V_{max}) remain relatively stable, the relation between these two parameters also remains stable and can be learned through experience (i.e., calibration). Thus the fact that minimum required speed in units of eye height is optically specified means that a properly calibrated observer can use such information to perceive minimum required speed as a proportion of V_{max}.

Third, the optical specification of required speed is invariant over changes in the actor's current speed. Thus regardless of whether one is moving quickly, moving slowly, or not moving at all, this variable specifies the speed at which one would need to move to intercept the target. This leads to the prediction that the ability to perceive the catchability of a target should be independent of how fast one is currently moving; that is, contrary to the current-future approach (e.g., see Oudejans, Michaels, Bakker, & Dolné, 1996), actors are not reliant on information that is only revealed by their actions. The findings of Fajen et al. (2011) summarized earlier are consistent with this prediction.

In summary, the current-future account and the affordance-based account rely on different optical variables that specify different properties of the actor-environment system (AES). Current-future accounts, such as the one that relies on the change in bearing angle, assume that actors are sensitive to the sufficiency of their current action, and assert that they must move to perceive whether a target is catchable. According to the affordance-based account, actors are sensitive to the speed required to intercept a moving target. The optical specification of this property does not depend on how the actor is currently moving. As such, the affordance-based approach asserts that actors are capable of perceiving catchability without moving at all.

Rationale and approach

Although evidence supporting the affordance-based account of catchability perception already exists (Fajen et al., 2011; Postma et al., 2014; Postma et al., 2017; Postma et al., 2018), the conclusions of those studies were based on perceptual judgments rather than on behavior during naturalistic interception tasks. The use of an action-based measure offers the opportunity to provide converging evidence and allay potential concerns about verbal judgments being noisy or contaminated measures of what actors actually perceive when they are engaged in a perceptual-motor task (Heft, 1993). In the present study, we designed a novel interception task wherein the ability to perceive target catchability while stationary was integral to successful performance. This allowed us to test predictions derived from the current-future and affordance-based perspectives about actual behavior that reflected how humans perceive whether a target is catchable and if pursuit is worth the effort.

The task was performed in a desktop virtual environment and was designed to emulate naturalistic situations that arise in both predator-prey behavior and sports. On each trial, a moving target crossed the subject's field of view heading toward a bamboo forest into which the target escaped. Subjects were instructed to intercept the target before it reached the forest if it was possible to do so, and to not pursue the target if it was uncatchable.

Our aim was to create a task that rewarded observers' sensitivity to target catchability while stationary, a common scenario in real-world interception tasks but one that is rarely examined in the literature. To this end, we introduced a point system (see Methods section and Table 1 for details) that incentivized subjects to pursue catchable targets, to not pursue uncatchable targets, and to abandon the chase as quickly as possible if they started to pursue a target and then perceived that it was uncatchable. Points were awarded after each trial in the form of a score, which was determined by subtracting points based on how far the subject moved during the trial (the movement cost) from points based on the outcome of the trial. Traveling a long distance to catch a target resulted in a small positive score, whereas a catch near the starting position resulted in a larger net gain owing to the lower movement cost. Abandoning the chase without moving at all resulted in a score of zero, which was the highest score that could be

Label	Description	Trial outcome (outcome reward/cost)	Movement (typical movement cost)	Typical trial score range (outcome + movement)
Catch	Subject pursued target until successful interception	Target intercepted (+10 points)	Yes (–5 to –8 points)	2–5 point gain
Miss	Subject pursued target until it escaped into forest	Target escaped (–2 points)	Yes (–3 to –8 points)	5–10 point loss
Pursue-and-give-up	Subject pursued target then gave up before it escaped	Subject gave up (0 points)	Yes (–1 to –5 points)	1–5 point loss
No-go	Subject gave up without moving	Subject gave up (0 points)	No (0 points)	0 points

Table 1. Trial outcomes and associated point values.

achieved on trials in which the target was uncatchable. Typically, catching a target earned subjects about half as many points as chasing and missing a target cost them, meaning that randomly chasing targets resulted in a negative cumulative score.

Experiment 1 was designed to test competing predictions derived from the current-future and affordance-based accounts about go/no-go decisions on this task. Current-future accounts rely on information that specifies target catchability only while the actor is moving. As such, they predict that subjects should initially pursue the targets on every trial. This may seem like a straw-man argument but in fact follows directly from Oudejans et al. (1996), who argued that actors do not have stored knowledge of their movement capabilities, and therefore need to move to perceive what they are capable of doing. In contrast, affordance-based control predicts that subjects should be able to discriminate between catchable and uncatchable targets before they start moving, albeit perhaps not perfectly. Thus in this task, subjects should decide to not move and quickly abandon the chase on most trials with uncatchable targets.

In Experiment 2, we examined competing predictions concerning the visual information that must be available for subjects to successfully complete the task. According to the current-future account, information about the sufficiency of one's current speed and heading is specified solely by the change in bearing angle. Therefore the manipulation of other variables—such as target-ground contact—should not affect performance. For an actor using an affordance-based strategy, removing target-ground contact should affect performance because the information that specifies minimum required speed is no longer available (see Figure 2).

Experiment 1

Methods

Subjects

Twenty naive subjects (6 women, 14 men) between the ages of 18 and 24 years participated in the study. Nineteen of the subjects received course credit and one subject received monetary compensation. All subjects were students from Rensselaer Polytechnic Institute, had a valid driver's license, and normal or corrected-to-normal vision.

Apparatus

The virtual environment was generated in Vizard 5.6 (WorldViz, Santa Barbara, CA) on an Alienware Area 51 desktop computer (Alienware, Miami, FL) with two GeForce GTX 480 graphics cards (NVIDIA, Santa Clara, CA), a 3.2-GHz Core i7 processor (Intel, Santa Clara, CA), and 6 GB of RAM running Windows 10 (Microsoft, Redmond, WA). The environment was displayed on an 27-in. monitor (ASUS, Taipei, Taiwan) at 1920 × 1080 resolution with a 60 Hz refresh rate.

Subjects sat in a chair approximately 1.0 m away from the screen, which subtended a visual angle of approximately 38°. The steering wheel and foot pedal system (Trackstar 6000; ECCI, Minneapolis, MN) was positioned at a comfortable distance in front of the chair. Subjects controlled their speed in the virtual environment via the foot pedal, such that speed was proportional to pedal position. The spring-loaded pedal provided resistance proportional to its distance from the neutral (up) position. When fully depressed, the subject moved at approximately 4.5 m/s within the virtual environment and stopped immediately on releasing the pedal. Subjects controlled steering by turning the steering wheel, the angle of which was related to path curvature by a proportionality constant of 6.36°/m.

Task and procedure

The virtual task environment consisted of an empty grassy field bordered on the right or left side by a bamboo forest, with a brown ground beneath a textureless black sky (Figure 3). The observer had a simulated eye height of 1.2 m.

Subjects pulled a paddle on the right side of the steering wheel to make the target appear. The target was a vertically oriented yellow cylinder with a radius of 0.05 m and a height of 2.0 m and was always in contact with the ground surface. After holding the paddle for 0.5 seconds, an audible "pop" sound was presented, indicating the start of the trial. The target then moved along a straight path toward the bamboo forest at a constant speed. One second after the target began to

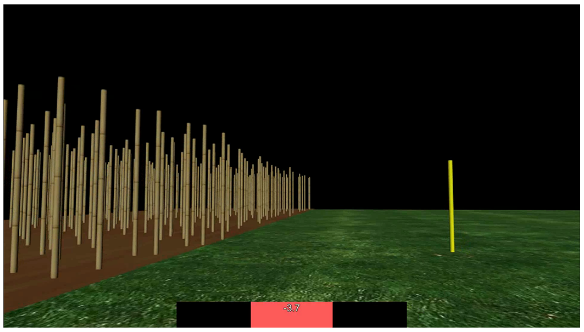

Figure 3. A screenshot of the task environment for a trial in Experiment 1. The cylinder on the right is the target, which moved at a constant speed right-to-left at a shallow approach angle on this trial. The score bar appeared at the bottom on the screen and displayed the current score throughout the trial, represented by both the length of the colored region of the bar and by the number at the center of the bar.

move a whistle blew, informing subjects that they were now allowed to move. Attempting to move by pressing the gas pedal during this preview period resulted in a false start, and the trial was reset. This provided subjects a short opportunity to perceive how the target was moving without trading off pursuit time.

Subjects were instructed to earn as many points as possible on each trial within the point system described next. There were two categories of point gains and losses—one based on how far the subject moved, and another based on the trial outcome (see Table 1). Points from the two categories were summed to determine the trial score. Movement points followed a single rule: subjects lost 0.5 points for every meter they moved. The points for trial outcome depended on whether the trial ended with the subject catching the target, with the target escaping into the bamboo forest, or with the subject giving up. Successful interceptions (catches) occurred when subjects moved within approximately 1.4 m of the target's center and were accompanied by a positive tone. If the target reached the bamboo forest before the subject caught it or gave up, the target escaped resulting in a "miss," and a negative tone was played. If subjects perceived that the target was no longer catchable, they could end the trial prematurely by pulling a paddle on the left side of the steering column at any time before the target reached the bamboo forest. This was accompanied by a neutral tone. We refer to such trials as "pursue-and-give-up," and those in which subjects gave up without moving as "no-go" trials.

A catch typically earned the subject two to five points and a miss typically lost them five to ten points, depending on how far they had moved. Pursue-and-give-up trials typically cost subjects one to five points, and no-go trials cost subjects zero points. The score was recorded after each trial and accumulated across trials within each block. The cumulative score was presented to subjects as a line graph at the end of each trial.

Design

The experiment comprised six blocks, each lasting about 5 minutes. Each block consisted of 30 trials and followed a fully crossed factorial design with five possible target escape times (2.3, 2.8, 3.3, 3.8, and 4.3 s) and six possible target escape points (10, 11.2, 12.4, 13.6, 14.8, and 16 m along the boundary between the field and forest). Figure 4 shows these possible escape points and their relation to the subject starting position. The target was catchable on 17 of the 30 trials per block; some were easily catchable, and others were catchable only if the subject started moving immediately, turned onto a path moving toward the escape point, and moved at maximum speed.

The distance from the target's position to the escape point was randomly varied between 10 and 25 m.

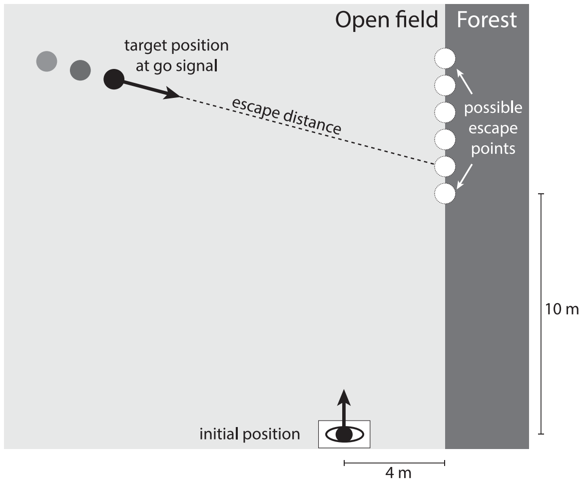

Figure 4. Schematic depiction of layout of virtual environment and main experimental variables. Subjects began each trial at the initial position and watched the target move for 1 s (preview period), after which the go signal was presented. The target moved at a constant speed toward one of six escape points along the boundary between the field and the forest. "Escape distance" refers to the distance between the target and the escape point at the moment that the go signal was presented.

The target moved at a speed ranging between 2.3 and 10.9 m/s, determined by the escape distance and the five possible escape times (2.3–4.3 s). The target approached the bamboo forest at a random angle between 50° and 75°. These values were all determined for the moment when the subject could start to move (i.e., at the end of the 1 s preview period). We accounted for the target preview period when calculating the target's starting position, such that the target moved at the aforementioned speed and distance to reach the escape point at the end of the trial.

Training

Prior to the beginning of the experiment, subjects completed a brief training phase with three training blocks. Difficulty was gradually ramped up by introducing new components of the task in each training block, which facilitated task engagement. In the first training block, they caught 10 separate moving targets with longer escape times (5.75–6.75 s). If a target escaped, the trial was reset until the subject successfully caught it. The subjects were not given the option to indicate the target as uncatchable or shown the score display during this block.

In the second training block, subjects gained the option to indicate that the target was not catchable, and responses were to be made as quickly as possible. There were 20 trials and escape time was varied such that targets were either clearly catchable (5–6.2 s) or clearly uncatchable (1–2 s). Distance to the escape point was either 10 or 13 m along the field/forest boundary. Subjects were required to complete each trial successfully and mistakes resulted in a trial reset.

In the third training block, subjects were presented with the score display and introduced to the scoring system. They were instructed to complete each trial with as high a score as possible, catching catchable targets and indicating uncatchable targets as soon as possible, possibly without moving. After subjects completed a training trial, the relevant trial outcome was explained. These explanations were scripted to ensure consistency across subjects and focused on making the scoring system as explicit and intuitive as possible. Trials in the final training block had escape times of 1.65 to 1.95 s or 3.6 to 5.2 s and escape points of either 10 or 13 m along the field/forest boundary. This range provided six uncatchable targets, more noticeably uncatchable than any in the experiment (2.3–4.3 s). The 3.6 s time to escape was comparable to the main experiment.

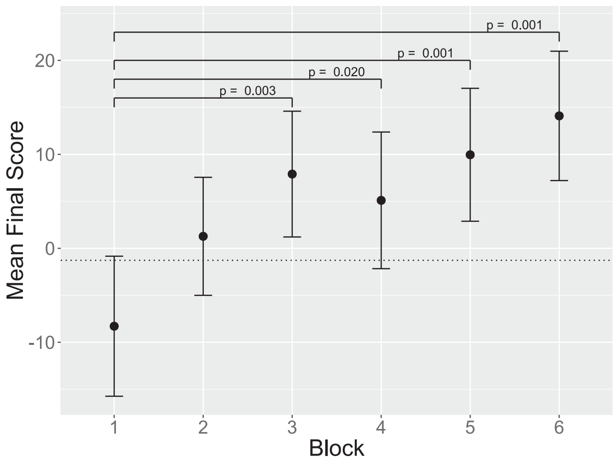

Figure 5. Mean final score by block for Experiment 1. Error bars are 95% CIs with between-subject variability removed. The *p* values correspond to difference from block 1 performance, corrected using Dunnett's adjustment. The dotted line indicates the CBA_{BD} model performance.

Results

Performance improved with practice

We first needed to confirm that subjects understood the task and determine how their overall performance changed over blocks. Given that subjects were instructed to maximize their point score, we chose the final scores in each block as our measure of performance. For the range of escape times and escape points used in this study, the maximum possible score that subjects could have attained was approximately 62 points. To earn this score, subjects would have had to pursue only those targets that were catchable and travel along a minimum distance path to the escape point. This assumes an ability to perfectly discriminate catchable and uncatchable targets, and make accurate go/no-go decisions within the 1 s preview period, which is not realistic. In practice, subjects sometimes pursued uncatchable targets and decided not to pursue catchable targets. Given that misses cost subjects about twice as many points as catches earned them (see Table 1), subjects would have to catch many more targets than they chased and missed just to earn a positive score.

Subjects initially performed poorly with negative block scores (*M*, –8.29; 95% confidence interval [CI], [–15.74, 0.84]), but improved with practice such that scores were well into the positive range by the sixth block (*M*, 14.09; 95% CI, [7.20, 20.98]) (Figure 5). Using a one-way repeated measures ANOVA, we found a significant main effect of block, $F_{5,95} = 5.55$, $p < 0.001$, $\eta^2_G = 0.12$. Looking at pairwise comparisons with block 1 as a control and using Dunnett's adjustment to control for type-I error rate inflation, we found significant differences for blocks 3, 4, 5, and 6. This improvement suggests that subjects learned to discriminate between targets to pursue and targets to let go. Several subjects scored much higher than the average on individual blocks. The highest score on any block was 50.74. In this top-scoring block, 15 of the 17 catchable targets were caught and all other trials were no-gos. During post-experiment debriefing, subjects reported confidence in their ability to perform the task.

Comparison with current-future strategy performance

Next let us consider how these scores compare to the predictions of the current-future account. To that end, we adapted the CBA model as it was implemented within the behavioral dynamics framework by Fajen and Warren (2007) to simulate the task in Experiment 1. Henceforth, we refer to this model as the CBA_{BD} model. The CBA_{BD} model embodies the current-future approach in that it relies on the change in bearing angle of a moving target to modulate angular acceleration while speed is held constant. The model typically generates smoothly curving trajectories that settle onto a straight path to the target. In its original form, the model lacks the ability to stop pursuing a target. As such, we altered the model to continue moving until it either caught the target or the agent's heading was beyond the target escape point (see Appendix A for more details). This is justifiable because once heading passes by the escape point, it is no longer possible to catch the target before it reaches the forest. Such trials were classified as pursue-and-give-up trials.

As prescribed by the current-future account, the CBA_{BD} model (adapted with the changes described

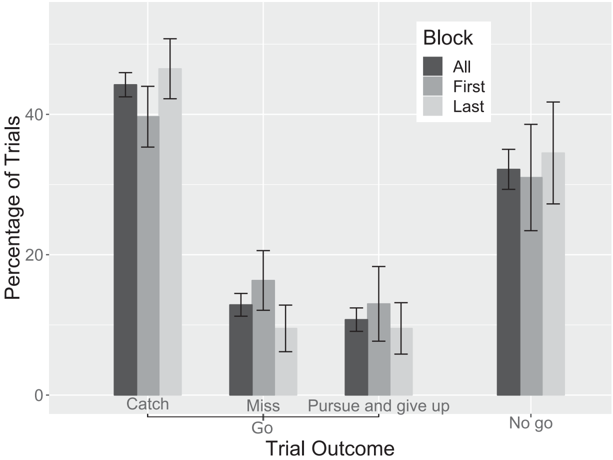

Figure 6. Mean percentage of each trial type in all blocks (black bars), block 1 (dark gray bars), and block 6 (light gray bars). Error bars indicate the 95% CIs with between-subject variability removed.

earlier) always chased the target for some distance. It successfully intercepted all catchable targets and gave up on remaining trials at some point before the target escaped, resulting in a mean final block score of –1.27 points (see dotted line in Figure 5). The fact that a score close to zero was attainable using current-future information is noteworthy because only the top scoring subjects reached this level of performance on the first block. Thus despite the use of a point system that disincentivizes unnecessary movement, it is not implausible that subjects could have adopted a strategy that requires them to move at least some distance on every trial to perceive whether the target is catchable. Based on score alone, we cannot rule out the possibility that subjects initially relied on current-future information to decide whether to pursue or not and when to give up.

Beyond block 1, the $\mathrm{CBA}_{\mathrm{BD}}$ model score fell within the subject CIs for the second and fourth blocks, and below those in the third, fifth, and sixth blocks. Because –1.27 is the maximum score attained by the $\mathrm{CBA}_{\mathrm{BD}}$ model, it follows that the strategy that subjects used (at least on later blocks) is not one that relies entirely on information about the current future.

Subjects typically caught the target or did not pursue

The black bars in Figure 6 show the proportion of catches, misses, pursue-and-give-up, and no-go trials averaged across all six blocks. On the majority of trials (76.4%), subjects either successfully caught the target or chose not to pursue it at all. The proportions of misses (12.9%) and pursue-and-give-up trials (10.8%) were relatively low. This distribution of trial outcomes is inconsistent with a current-future account, which predicts that subjects will initially pursue the target on all trials (i.e., zero no-go trials).

To better assess the accuracy of decisions, we examined how decisions to initially pursue the target or not, and to give up during pursuit, were related to the initial catchability of the target. On trials in which subjects chose not to pursue the target (i.e., no-go trials), the target was uncatchable 76.6% of the time. When they did initially pursue the target (i.e., combining catches, misses, and pursue-and-give-up trials), it was catchable 76.2% of the time. Breaking this down further, we found that the percentage of catches, misses, and pursue-and-give-up trials on which the target was initially catchable was 100%, 45.5%, and 16.7%, respectively.

Given that final block scores were initially indistinguishable from those that could have been attained using current-future information, one might wonder if subjects initially adopted a current-future strategy (pursuing targets on all trials) and learned a different strategy over time that yielded higher scores. If such a strategy shift occurred, we would expect to see a shift in the distribution of initial go/no-go decisions across blocks (e.g., very few no-gos in early blocks, and more on later blocks). However, Figure 6 shows qualitatively similar trial outcomes in the first and last blocks (dark gray and light gray bars). That is, there is no evidence that subjects drastically altered their strategy throughout the experiment; instead they appeared to have refined their initial strategy as they became more familiar with the task.

Sensitivity to target catchability

Based on the trial outcome analysis, we know that on the majority of trials, subjects either pursued and intercepted the target or chose not to pursue it at all. According to the affordance-based account, such behavior reflects sensitivity to information about the minimum speed needed to intercept the target. When actors are calibrated to their speed capabilities, they are in principle able to use such information to perceive the proportion of the maximum speed that is needed to intercept the target. As such, their go/no-go decisions should reflect the catchability of the target. Given that go/no-go decisions are made while the actor is stationary, sensitivity in these decisions to target catchability (if it exists) cannot be explained by a current-future account.

We tested this prediction by plotting the proportion of go/no-go decisions (collapsed across blocks) as a function of target catchability, which we operationally defined in terms of the minimum speed required to intercept the target at the moment that the subject was allowed to start moving. We then fit a psychometric curve to each subject's data, and calculated the critical value at which the proportion of go/no-go decisions

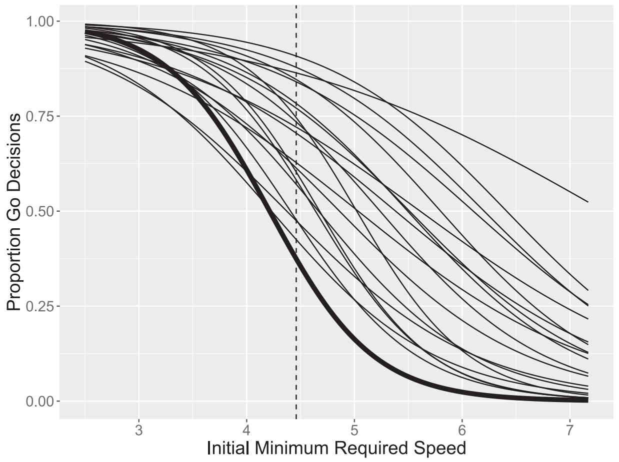

Figure 7. The best-fitting curves for each subject's go/no-go decisions (collapsed across blocks) as a function of initial minimum required speed to catch, which provides a measure of target catchability. The bold curve corresponds to the subject with the highest overall score. The dotted line shows the maximum speed at which subjects could move (4.46 m/s).

was 50%. Figure 7 shows the best-fitting curves for each subject. As expected, as the initial minimum required speed increased (i.e., as the target became less catchable), subjects were less likely to pursue the target. This was consistent across subjects.

Although this trend was consistent across subjects, it is clear from Figure 7 that there was also some variability between subjects. Differences in the slope of the best-fitting curve could be attributed to variation in the degree of attunement to information about target catchability. Although the information described in Figure 2 unambiguously specifies target catchability, it is likely that some subjects were better attuned to such information than others. Those who were well attuned and properly calibrated to their speed capabilities would be better able to discriminate between catchable and uncatchable targets than those who were not well attuned. Consistent with this interpretation, we also observed that the goodness of fit of the best-fitting curve decreased systematically with slope (r, 0.974; $p < 0.001$). Likewise, differences in the critical points could be attributed to variation across subjects in tolerance for risk. On any given trial, subjects had to quickly choose whether to pursue the target or not by weighing the benefits of catching against the costs of missing. It is likely that some subjects were more willing to take that risk than others simply due to factors such as personality differences.

Although the critical value for the highest scoring subject (~4.2 m/s) was very close to the maximum possible speed (4.46 m/s), the critical value for many subjects fell well above this cutoff, reflecting a tendency to sometimes initiate movement even when the target was uncatchable. This may seem inconsistent with an affordance-based account, and perhaps even suggest a preference to move to reveal current-future information. In the next section, however, we propose how this apparent inconsistency can be reconciled within the affordance-based approach.

Why did subjects pursue uncatchable targets so often?

Figure 8A displays the proportion of go responses for each combination of escape time and distance. As expected, the proportion of go responses was high on trials in which escape time was long and the escape point was nearby (lower-right corner), and low when escape time was short and the escape point was far away (upper-left corner). Of note are the three squares marked with stars. For these conditions, the target was no more difficult to catch than it was for the two conditions marked with diamonds (i.e., the initial minimum required speeds were very similar). Nevertheless, subjects chased targets in conditions marked with stars more than 50% of the time. Further, for two of the conditions marked with a star, targets were less catchable than for the condition marked with a triangle yet were pursued more often. Even the top scoring subject (Figure 8B) chased the target on some of these trials.

These findings reveal that when subjects chased after uncatchable targets, they did so more often in conditions in which the initial distance to the escape point and the initial escape time were longer. Such behavior could be explained as a consequence of detecting the relevant optical information with a level of precision that decreased with both escape time and target distance. In other words, when subjects chose whether to pursue the target on a given trial, they may have done so based on an estimate of target catchability that was not perfectly precise and that decreased in precision with distance. Thus subjects may have occasionally perceived that uncatchable targets were initially catchable, and hence chose to pursue them. Further, the likelihood of this occurring may have increased as target distance and escape time increased.

To test the plausibility of this interpretation, we used a Bayes filter to model the go/no-go decisions of an agent that perceives target catchability but with variability that increases with both escape time and target distance (see Appendix B for details). The model relied on a grid approximation of the likelihood of the target being catchable given the values of four variables that can be used to determine target catchability. The likelihood of target catchability was approximated by calculating the value of four variables at each time point in simulated trials, as well as whether the target was catchable at that time. This was done for approximately 3 million simulated trials generated

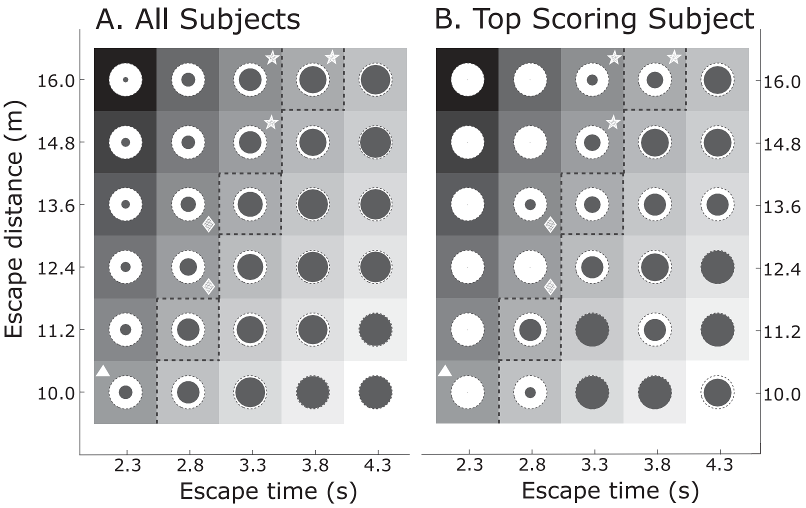

Figure 8. Mean proportion of trials in which subjects chased the target for any distance represented by diameter of the black circles as a function of target escape distance (y-axis) and escape time (x-axis). The shade of the squares corresponds to the initial minimum required speed for that condition: a dark square indicates very uncatchable, and a light square indicates very catchable. The dotted black line separates conditions in which targets are catchable (top left) from conditions in which targets are uncatchable (bottom right). For the three squares enclosed by the dotted lines, the target was catchable but only barely so requiring a very short reaction time and straight-line path to the interception point. (A) shows the average across all subjects and (B) shows the top-scoring subject. See main text for explanation of star, triangle, and diamond symbols.

by randomly combining target and subject paths from 19 subjects, leaving the trials seen by the 20th subject for validation. The result of this process was a large matrix of catchability likelihood estimates for which the relative proportion and covariance of individual visual variables reflected that of the task. This allowed us to determine how often the target was catchable given specific values for the four variables.

To simulate uncertainty, we introduced noise into the model by convolving an isometric Gaussian kernel across the grid of catchability likelihood estimates. The increments of the grid along each dimension were evenly spaced in log-space. As such, the kernel, which was convolved across the same number of grid indices, corresponded to a wider range at higher values of a variable. Thus the noise increased in proportion to the value of the variable. The likelihood was then used to determine the agent's perceived target catchability (expressed as a proportion) for every time step of a trial. For the model results presented later, we used the trials of the subject whose data were set aside when building the likelihood estimate.

The agent's go/no-go decision was based on a simple rule that was applied 200 ms after the end of the preview period: chase the target unless perceived target catchability was less than 1.0 by a small threshold value (0.001). That is, the agent pursued the target if, and only if, perceived catchability was greater than 0.999. We used 0.999 because when the agent was stationary and perceived catchability decreased, it dropped quickly from 1 to 0. As such, this threshold marked the beginning of the transition from perceived catchable to perceived uncatchable.

Figure 9A shows the proportion of go trials as a function of initial minimum required speed to catch the target. Although the best-fitting curve is steeper than those for human subjects (Figure 7), the agent did initiate movement on trials in which the target was uncatchable. Similar to human subjects, this occurred more often when escape time and distance were longer (see Figure 9B). Thus by assuming that the precision of perceived target catchability decreases with increasing target distance and escape time, we can capture within the affordance-based framework the observed tendency to sometimes initiate movement on trials in which the target is uncatchable.

Summary

The main finding from Experiment 1 was that subjects made go/no-go decisions that revealed sensitivity to the catchability of the target. On trials in which the target was catchable, subjects usually pursued and successfully intercepted the target; when the target was uncatchable, they often chose not to move at all. Occasionally, subjects initially pursued uncatchable targets. This tended to occur when the target was initially far away (in both space and time) from the escape point, and can be attributed to variability in the detection of information about the speed needed

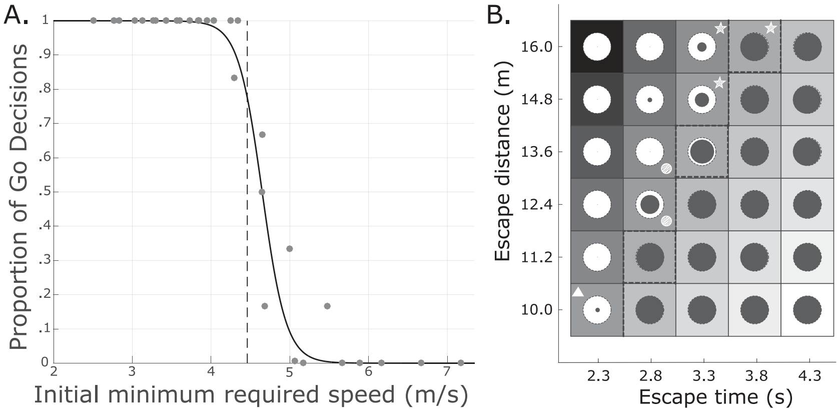

Figure 9. (A) Proportion of go trials generated by the probabilistic model as a function of initial minimum required speed. (B) Mean proportion of trials in which the model agent chased the target for any distance represented by diameter of the black circles as a function of target escape distance (y-axis) and escape time (x-axis). See Figure 8 caption for additional details.

to catch the target. On about half of such trials, subjects gave up before the target reached the escape point, suggesting that perceived catchability became more precise as they drew closer to the target and as the target drew closer to the escape point. The fact that subjects were able to make accurate go/no-go decisions on the majority of trials is consistent with an affordance-based account, according to which actors rely on information that specifies target catchability independently of the actor's movement. The findings are also difficult to reconcile with an account based entirely on current-future information, which is uninformative about target catchability while the actor is stationary. Furthermore, there is no evidence that subjects began the experiment by using current-future information to perceive catchability, and then switched to affordance-based information with practice. Even in block 1, subjects made go/no-go decisions that revealed sensitivity to target catchability.

Experiment 2

Experiment 2 tested competing predictions derived from the affordance-based and current-future hypotheses about the visual information that must be available to perform the task. A current-future account based on the change in bearing angle requires only that the observer can detect the change in the target's direction with respect to an arbitrary reference direction. In contrast, the affordance-based account relies on a composite optical variable that includes the angle of declination (see Figure 2), and is therefore only available when the target is in contact with the ground plane. Hence if actors rely on affordance-based information, performance should be worse when the target is floating and the point of contact with the ground plane does not exist. Conversely, the current-future account predicts that behavior should be unaffected by any manipulation of target-ground contact because the relevant information is available regardless of whether the target is floating or grounded.

To test this prediction, we compared performance on the same task as Experiment 1 under two conditions (depicted in Figure 10): one in which the target was a sphere floating in the air (floating sphere condition) and the other in which the target was a sphere supported on the ground plane by a post (grounded sphere condition).

Methods

Subjects

Twenty naive subjects (10 women and 10 men between the ages of 18 and 21 years) participated in the experiment. None of the subjects participated in Experiment 1. Six of the subjects received course credit and 14 subjects received monetary compensation. All subjects were students from Rensselaer Polytechnic Institute, had a valid driver's license, and normal or corrected-to-normal vision.

Task and procedure

The task, procedure, and design of Experiment 2 were the same as in Experiment 1 with the following exceptions. First, we manipulated the shape of the target to be either a floating sphere or a grounded sphere (Figure 10). The spheres were centered at the simulation eye height (1.2 m) in both conditions. The

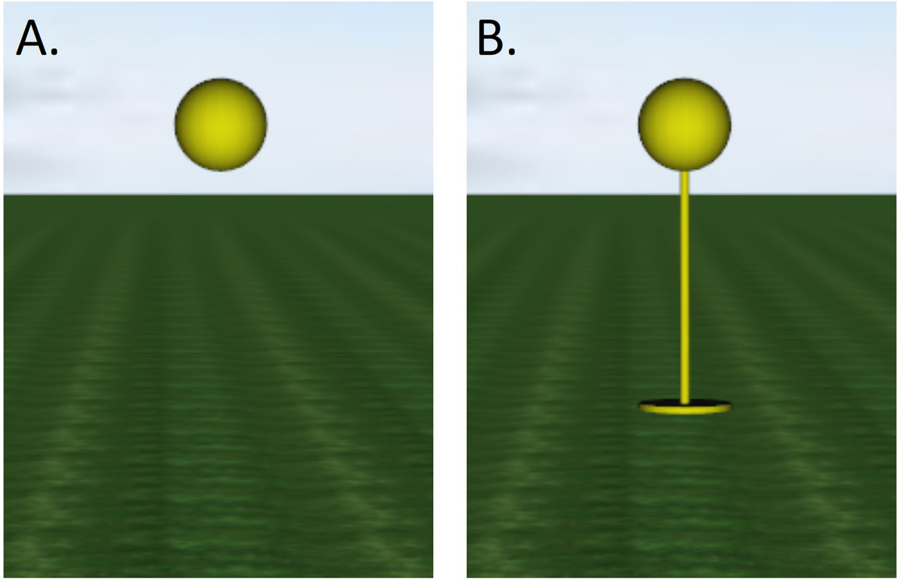

Figure 10. Target shapes used in Experiment 2: (A) the floating sphere condition, (B) the grounded sphere condition.

target in the grounded sphere condition included a circular base half the radius of the sphere directly beneath the sphere on the ground. These two shapes were joined by a vertical cylindrical post. Second, the radius of the sphere on each trial was randomly varied within the range 0.1 to 0.5 m in both conditions. This prevented subjects from using familiar size to estimate their distance to the target, which could have partly negated the intended effect of the target shape manipulation. Third, target shape was fixed within each block but alternated across blocks, with half of the subjects starting in the floating sphere condition and the other half starting in the grounded sphere condition. Fourth, the training phase was altered such that subjects were always trained on the condition that was used in the first block and were not informed until the second block that the shape would change. Finally, a sky with clouds was added to provide a rich visual reference against which the change in target's bearing angle could be detected (see Figure 10).

Results

After each experimental session, we asked subjects what they thought of the task and if they had any questions. During this informal debriefing, all subjects stated without prompting that the floating sphere condition was extremely difficult compared with the grounded sphere condition. During pilot testing, we were compelled to alter the wording of the training instructions to ensure that subjects did not get discouraged by how difficult the floating sphere condition was. We mention these anecdotes because they convey the perceived difficulty of the floating sphere condition.

Performance was poor in the absence of target-ground contact

First, we examined if there were any differences between conditions in overall task performance. Recall that if subjects relied on the change in bearing angle, there should be no difference in scores across the conditions, and if subjects used affordance-based information, performance should be degraded in the floating sphere condition. This observation is borne out in the mean final scores in each block (Figure 11). A two-way repeated-measures analysis of variance revealed significant main effects of both block, $F_{2,38} = 4.52$, $p < 0.05$, $\eta^2_G = 0.04$, and target type, $F_{1,\,19} = 138.78$, $p < 0.001$, $\eta^2_G = 0.42$. The block × target type interaction was not significant, $F_{2,\,38} = 1.57$, $p = 0.22$, $\eta^2_G = 0.02$. Simple main effects analysis revealed that the effect of target type was significant ($p < 0.001$) for all three blocks, indicating that performance degraded when the target was not in contact with the ground.

No-gos and misses were more frequent in the floating sphere condition

The distribution of trial outcomes in the grounded sphere condition (see gray bars in Figure 12) was similar to that in Experiment 1, with subjects catching the target or choosing not to pursue it on the majority of trials. In the floating sphere condition (black bars), the proportion of pursue-and-give-up trials

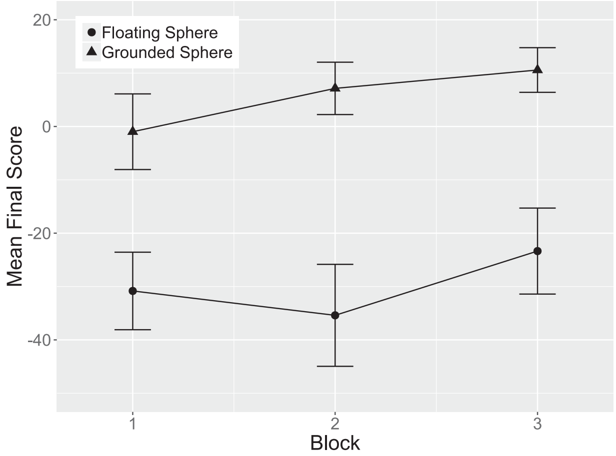

Figure 11. Mean final score by block for both the grounded sphere (triangle) and floating sphere (circle) conditions. Error bars indicate 95% CIs with between-subject variance removed. The block numbers signify order within the condition.

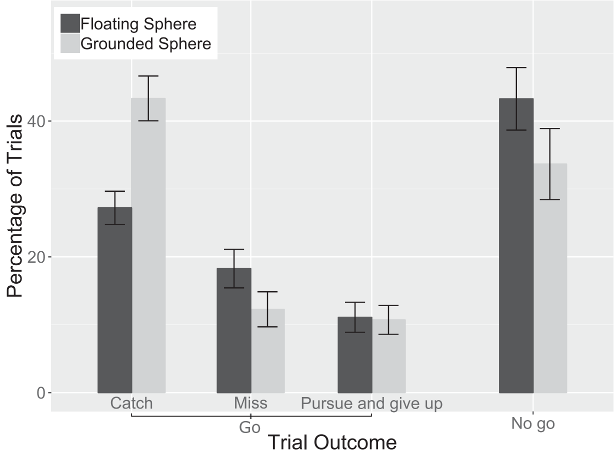

Figure 12. Mean percentage of trials of each outcome collapsed across blocks for the floating sphere condition (black) and grounded sphere (gray) in Experiment 2.

was similar to the corresponding proportions in the grounded sphere condition (mean difference [M_{diff}] between conditions, 0.38%; 95% CI, [–1.94, 2.72]), but subjects caught the target less often (M_{diff}, –16.11%; 95% CI, [–19.98, –12.24]) and missed it more often (M_{diff}, 6.00%; 95% CI, [3.08, 8.92]). This suggests that when subjects pursued the target, they struggled to successfully regulate their speed and direction in the absence of target-ground contact. They also chose not to pursue the target more often (M_{diff}, 9.61%; 95% CI, [4.19, 15.04]), suggesting that they adopted a more conservative strategy. Interestingly, the two subjects who scored the highest on the last block of the floating sphere condition chose not to go on approximately 70% of trials; that is, they adopted a highly conservative strategy that allowed them to avoid point losses.

General discussion

Humans do not need to move to perceive catchability

The aim of this study was to test two competing theoretical accounts of how actors perceive the catchability of moving targets and choose whether to pursue them: the current-future account and the affordance-based account. A central issue that distinguishes the two accounts is the property of the AES on which the choice is based. The current-future account asserts that actors perceive the sufficiency of their current state, which by definition is dependent on how one is currently moving. As such, current-future information cannot be used to perceive whether a target that is uncatchable at the current speed would be catchable if one were to move at a faster speed. This includes the case when one's current speed is zero; that is, before movement is initiated, actors relying on current-future information cannot perceive the catchability of the target. In contrast, the affordance-based account asserts that actors perceive the speed needed to catch the target in relation to their maximum possible speed. Unlike the sufficiency of one's current speed, the minimum speed required to intercept is independent of one's current speed of self-motion. This property is specified by information that is available regardless of whether the actor is stationary or moving (Fajen, 2013). As such, this information can be used to perceive catchability both before and after movement is initiated. This leads to competing predictions about the necessity of movement in perceiving the catchability of moving targets.

The evidence from the present study clearly shows that humans can perceive catchability before initiating movement. Even in the first block of the experiment, subjects pursued and successfully intercepted most catchable targets and chose not to pursue most uncatchable targets. The results are consistent with findings from previous studies (Fajen et al., 2011; Postma et al., 2014; Postma et al., 2017; Postma et al., 2018) in which subjects made perceptual judgments of the catchability of fly balls or the passability of shrinking gaps. The novel contribution of this study is the use of a task for which the perception of catchability while stationary is integral to successful performance, allowing for evidence in the form of behavior rather than perceptual judgments.

Strategies for online guidance

The task used in the present study required subjects to both decide whether to pursue the target and regulate self-motion to intercept the target. Nevertheless, the primary focus of our analysis was on action selection (i.e., the go/no-go decision). As such, one might wonder about the strategy that actors use to guide locomotion once movement is initiated.

One possibility is actors rely on current-future information, such as the change in bearing angle. This amounts to a hybrid account in that actors rely on affordance-based information to decide whether to pursue the target, and current-future information to guide locomotion once movement is initiated. Such an account would be compatible with the framework described by Warren (1988), which distinguishes between the problem of perceiving the affordances for a given situation and selecting an appropriate action to realize, and the problem of regulating force-related parameters of the action system based on optical information. In the terminology used by Warren, perceiving whether the target is catchable and deciding whether to initiate a pursuit amounts to solving *the affordance problem*, and modulating speed and direction of locomotion based on the available information to intercept the target amounts to solving *the control problem*. Recently, Lin & Leonardo (2017) proposed that dragonflies use one set of heuristics to determine whether to pursue prey and when to initiate takeoff, and another strategy for guiding pursuit.

We see two potential challenges for such a hybrid account of the behavior observed in the present study: one empirical and one theoretical. First, if actors rely entirely on current-future information once movement is initiated, we would expect that when subjects pursued the target in Experiment 2, they should perform just as well in the floating sphere and ground sphere conditions. In fact, on trials in which subjects pursued the target, they were almost twice as likely to miss the floating sphere target ($\sim$32%) compared with the ground sphere target ($\sim$18%). This disparity cannot be attributed to a difference in response time—on trials in which subjects pursued the target, the time to initiate movement was not significantly different between the two conditions (M, 0.383 s; 95% CI, [0.372, 0.393]) and (M, 0.389 s; 95% CI, [0.372, 0.406]) in the grounded sphere and floating sphere conditions, respectively; $t(19) = 0.918$; $p = 0.370$.

Second, possibilities for action (i.e., affordances) do not cease to be important after movement is initiated (Fajen, 2005; Fajen, 2007). Regardless of whether one is preparing to move or pursuing a target, one must know whether it is within one's capabilities to intercept the target before it escapes. As discussed in the Introduction, even for a moving observer, current-future information can only specify catchability in a very limited sense (Fajen, 2013). For example, if the pursuer is moving at moderate speed and the bearing angle is shrinking, the change in bearing angle specifies that the actor's current speed is insufficient to intercept the target for the given direction in which the actor is currently moving. It does not inform the actor about which of the following is the actual state of affairs: (a) the target is catchable by increasing locomotor speed and continuing to move in the same direction, (b) the target is catchable but only by both increasing locomotor speed and turning farther ahead of the target, or (c) the target is uncatchable. Such information is critical to properly coordinating speed and direction of locomotion during interception (Bastin, Fajen, & Montagne, 2010) and making proper decisions about whether to continue to pursue the target or give up.

If current-future information alone is not sufficient to account for online visual guidance in this task, what information and control strategies did subjects use? One possibility is that actors rely on affordance-based information to make the initial pursuit decision and both types of information after movement initiation. For example, current-future information could be used to guide change in speed and direction of self-motion, while affordance-based information could be used to ensure that it remains possible to catch the target (e.g., if an adjustment to speed or direction was made improperly, if target trajectory changed).

Another possibility is that actors attempt to maintain a CBA while moving in a direction that keeps the time-to-contact with the target less than the amount of time remaining until the target reaches the escape point (i.e., escape time). A critical open question that would need to be answered for such an account to be viable is how actors estimate escape time. One might assume that actors could rely on a τ-like variable based on the visual angle between the target and the escape point and its rate of change. However, in the present study, the escape point was unmarked and varied from trial to trial so it would have to be estimated from the available information. In addition, the change in the visual angle between the target and the escape point is also affected by the observer's movement, which contaminates the relation between the "τ" of that angle and escape time.

A third possibility is that actors rely on affordance-based information for both the initial go/no-go decision and online visual guidance. For example, actors could move in the direction for which the optically specified minimum required speed is equal to the desired locomotor speed. Evaluating these alternative accounts of online guidance is beyond the scope of the present study but deserves consideration in future research.

Did the point system unfairly bias subjects away from using current-future information?

Given that subjects lost points for moving, one might wonder if the point system unfairly disincentivized subjects from relying on current-future information for go/no-go decisions. We offer two counterarguments to this concern. First, although points were deducted for moving, the point system did not disincentivize movement per se. Rather, it disincentivized subjects from pursuing uncatchable targets. Subjects were told that their goal was to accrue the most points possible, and the only way to complete a block with a positive score was to pursue catchable targets and not pursue uncatchable targets. As such, the point system incentivized perceptual sensitivity to target catchability. If moving is critical for the accurate perception of catchability, as suggested by the current-future account, then the point system would have incentivized subjects to move on every trial (even if only for a period long enough to reveal current-future information about catchability).

Second, this concern would only be valid if we had simply created an arbitrary, artificial point system that biases subjects toward a particular strategy. That was not the case. In fact, the main purpose of the point system was to create incentives that align with those of naturalistic locomotor interception tasks. If the system disincentivized the kind of behavior that is predicted by current-future strategies, that implies a shortcoming of the current-future account rather than a problem with the point system. Likewise, if the only way to elicit behavior that is consistent with the current-future account is to make these incentives irrelevant (e.g., by requiring that subjects pursue the target on every trial, as in most previous studies), the viability of the current-future account as a theory of real-world locomotor interception must be questioned.

Target-ground contact is advantageous for successful interception

The fact that performance in Experiment 2 was so dramatically impacted when the target was floating rather than in contact with the ground plane has broader theoretical significance. When the target is in contact with the ground, spatial properties, such as target size and distance, are specified in units of eye height, allowing for the perception of these dimensions in relation to dimensions of the body (Lee, 1980; Warren, 2007). The fact that manipulations of eye height affect perceptual judgments of spatial properties (Mark, 1987; Warren & Whang, 1987; Wraga, 1999) indicates that eye height–scaled information plays a key role in the perception of spatial layout. In the context of locomotor interception, target-ground contact makes information available about the minimum speed required to intercept the target in units of eye height per unit time (Fajen, 2013). This is what makes it possible for actors to perceive minimum required speed in relation to maximum possible speed. Specifically, to the degree that the relation between eye height and maximum locomotor speed (V_{max}) remains stable, optical information specifying the ratio of minimum required speed to eye height also provides information about the ratio of minimum required speed to V_{max}.

Probabilistic perception of affordances

Affordances are traditionally construed as categorical: a target is either catchable or it is not. However, variability in the execution of movement raises the possibility that catchability is actually a continuous, probabilistic function. In their treatment of affordances as probabilistic functions, Franchak and Adolph (2014) proposed that the perception of affordances may also entail perception of the probability of success given the state of the environment and variability in the motor systems.

In the present study, we considered a related issue—the possible probabilistic nature of affordance perception resulting from variability in the detection of information. In Experiment 1, subject's go/no-go decisions were sensitive to the catchability of targets, and yet subjects sometimes pursued uncatchable targets. A disproportionate number of such doomed pursuits occurred on trials in which the target's initial distance to the escape point and escape time were long. As our mathematical model demonstrates, these are precisely the conditions in which variability in the detection of optical angles and their rates of change would most significantly impact the perception of catchability. Although pursuing an uncatchable target is costly, so is failing to pursue a catchable target. As such, when catchability is perceived with less precision, it may be beneficial to initiate movement, knowing that precision will increase over time as the target approaches the escape point, and that pursuit can be quickly abandoned if it becomes clear that the target is uncatchable.

It is worth noting that our model does not consider motor variability or its effects on affordances and affordance perception, as outlined by Franchak and Adolph (2014). As such, the model chooses to pursue catchable targets regardless of how precise the actor's movements would need to be to intercept the target. By further developing the model, it might be possible to better capture human go/no-go decisions. The model could also be used to generate predictions of perceived catchability at each point along the human trajectories, allowing one to predict the point at which subjects know to give up the chase of an uncatchable target. Together with the understanding of affordances as probabilistic functions owing to motor variability (Franchak & Adolph, 2014), this represents a potentially fruitful new direction for affordance perception.

Keywords: affordance-based control, constant bearing angle strategy, go/no-go, interception, visual control

Acknowledgments

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Footnotes

[1] A prior study using a similar paradigm (Oudejans et al, 1996) reported that judgment accuracy was higher when subjects were allowed to move. However, Fajen et al. (2011) identified methodological problems that explain the difference in the accuracy of judgments while subjects were stationary versus moving, and demonstrated that these differences vanished when the methodological problems are addressed.

[2] Note that minimum required speed is optically specified for any arbitrary direction of locomotion (see Fajen, 2013).

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Appendix A

We adapted the CBA model of interception from Fajen and Warren (2007) to simulate the task of Experiment 1. The model generates trajectories to intercept moving targets based on the change in bearing angle. We modified the model agent's speed to match the maximum speed of subjects in the present study (4.46 m/s), and maximum turning rate was matched to the maximum turning rate in the experiment (6.36°/m). Target trajectories qualitatively matched those from the actual experiment.

The model agent began each trial in the same location and orientation as human subjects. One second after the target began to move (i.e., at the end of the preview period), the model agent began moving at 4.46 m/s with an angular acceleration determined by the CBA_{BD} model. If at any point before catching the target the agent's heading turned past the escape point by more than the catch radius, the trial was terminated and classified as a pursue-and-give-up trial. Otherwise, the trial ended in a catch, which occurred when the agent was within 1.4 m (the catch radius) of the center of the target. The score for each trial was based on how far the model moved and the trial outcome, using the same point system as in the actual experiment.

The CBA_{BD} model has three parameters, which were originally fit to human data from Fajen and Warren (2004). Because the purpose of this simulation analysis was to determine the highest possible score using a CBA strategy, we refit the parameters using a grid search to find the set of parameters that resulted in the highest mean final block score for the six blocks completed by a randomly selected subject from Experiment 1. The best-fitting parameters were $b = 0.5$, $k = 19$, and $c = 24$. When these parameters were used to simulate trials completed by human subjects, the overall mean block score was nearly identical (*M*, –1.27; *SD*, 0.04).

Appendix B

The aim of this analysis was to determine whether imprecision in perceived catchability is a plausible explanation for the observation that subjects sometimes pursued uncatchable targets. The model maintained an estimate ($\hat{X}_t$), which was a value between 0 and 1, representing the estimated probability that the target was catchable. This estimate was maintained by iteratively applying Bayes' rule such that the posterior at time step t-1 became the prior at time step t. This led to the following update rule:

$$\hat{X}_t = \frac{P(\vec{Z}_t|\mathrm{X}_t) \bullet \hat{X}_{t-1}}{P(\vec{Z}_t)} \quad \text{(B1)}$$

where t is the time step, X_t is a binary variable corresponding to the actual catchability of the target, and $\vec{Z}_t$ is a vector of four variables of the AES: (a) distance from the agent to the target, (b) the amount of time remaining until the target reached the escape, (c) the distance from the target to the escape point, and (d) the minimum distance from the agent to the segment of the target's trajectory between the first position where the target is catchable and the escape zone. Applying the update rule resulted in a time series of the estimated probability that the target was catchable at each time step of simulated trials.

$P(\vec{Z}_t|\mathrm{X}_t)$ is the *likelihood*, or the probability of observing particular values of the four AES variables given that the target is actually catchable ($X_t = 1$) or not ($X_t = 0$). $P(\vec{Z}_t)$ is the normalization term. Analytically calculating the likelihood and normalization term is intractable. As such, before applying Equation B1, we estimated the likelihood and normalization term using grid approximation. This entailed a multistep process, the details of which we describe next.

Grid approximation

The first step was to initialize a large matrix (Ω) with five dimensions: one for each of the four AES variables and one for X, the binary variable corresponding to target catchability. Values in the matrix were initialized to zero but came to equal the frequencies of observing all possible combinations of the four AES variables when the target was catchable and when it was uncatchable. Cells in Ω were filled in using data from simulated trials. Because the number of cells in the matrix was so large, we needed many more trials than were completed by human subjects. As such, we generated new combinations of paths by splitting the data from each trial completed by 19 of the 20 subjects (subjects 2 through 20) in Experiment 1 into a list of subject paths and a list of target paths. We then randomly paired subject and target paths from different trials, truncating to the shorter of the two paths. This sampling process resulted in an arbitrarily large number of unique combinations of subject and target paths without creating scenarios that could not arise in the experiment, such as the agent being in a particular position at a particular time that a human subject could not have reached, even by moving at the maximum speed. This also preserved the inherent relationship between AES variables because the generated trials were real situations that could have arose during the experiment.

There were some sampling biases introduced in the later portions of the trials when the target is close to the escape point. Because of having used real subject data, as well as truncating to whichever of the two randomly selected paths was shorter, whenever subjects made a catch or gave up the trial ended early, and thus we had fewer examples of the later stages of the trial than of the beginning. Furthermore, these generated trials are less likely to be in a catchable state when the target is near the escape point because the subject path was based on (and likely near) a different escape point. However, the effect of this bias on our analysis was minimal because the undersampled portion of the space generally corresponded to situations that arose during the latter portion of trials, and our focus was on the go/no-go decision, which occurred near the beginning.

Next we calculated, for each timestep of each trial, the values of the four AES variables and whether the target was still catchable given the positions of the agent and the target. Note that this was whether the target was actually catchable, and not whether a subject actually caught it. These five values were used to determine the indices of a cell of Ω whose value was incremented by one. For example, if at a particular time step, target distance was 5 m, escape time was 3 s, escape distance was 10 m, minimum distance to the target path was 3 m, and the target was catchable, the value of the cell of Ω with indices [12, 34, 26, 8, 1] was increased by one. When this process was complete, Ω held the counts of the number of times any given combination of values of AES variables was observed when the target was catchable and when it was uncatchable.

Bins of Ω along each of the four AES variable dimensions were evenly spaced in log-space with cutoffs determined by the logspace function in MATLAB (MathWorks, Natick, MA). The number of bins was set to 40, and the minimum and maximum values for each variable are shown in Table B1. To avoid extremely small bin sizes, which would be difficult to populate, we set a lower bound on bin size for each variable, and increased the size of any small bin to equal the lower bound. Values for the lower bound and the number of bins whose sizes were adjusted are also shown in Table B1.

We generated trials in batches of 10,000, calculated $\vec{Z}_t$ and X_t for each time step, and updated Ω. These steps were repeated while tracking the sparsity of Ω for 300 batches, at which point generating additional trials led to negligible reductions in sparsity. Next Ω was convolved with a 4-D isometric Gaussian noise filter ($\sigma = 1$ cell), which added noise in proportion to the magnitude of the value of each component of $\vec{Z}_t$.

On completion of this process, the values of Ω approximated the frequencies of observing all possible combinations of the four AES variables when the target was catchable and when it was uncatchable. Next we used Ω to estimate $P(\vec{Z}_t \mid \mathrm{X}_t)$ (the likelihood) and $P(\vec{Z}_t)$ (the normalization term) for each cell of Ω. The likelihood was estimated by first conditioning on X_t, specifically $X_t = 1$ because we were interested in the probability that the target was catchable. We then divided the value of each cell by the sum of the counts across Ω [:, X_t = catchable], yielding the probability of observing values of $\vec{Z}_t$ within the ranges for that cell given that the target was catchable. The process for estimating $\mathrm{P}(\vec{Z}_t)$ was similar except that we did not condition on X_t.

Model simulation

We then iterated through trials completed by subject 1, calculating the AES variables at each time step ($\vec{Z}_t$) and updating the model's catchability estimate ($\hat{X}_t$) using Equation B1. The estimate at $t = 0$ was set to 17/30 because 17 of the 30 trials in each block were catchable. This process resulted in a time series of catchability estimates for each trial completed by subject 1. We then used these time series to determine the go/no-go decision as follows. If $\hat{X}_t$ when $t =$ 1.2 s was greater than or equal to 0.999, the trial was classified as a go; otherwise, the trial was classified as a no-go. We chose 1.2 s because 200 ms is a plausible estimate of reaction time, and close to the earliest time at which subject 1 pulled the "give up" paddle on a trial. We chose 0.999 as a threshold because when the agent was stationary and estimated catchability decreased, it dropped quickly from approximately 1 to approximately 0. As such, 0.999 marked the beginning of the transition from catchable to uncatchable.

AES variable name (units)	Minimum	Maximum	Lower bound	# adjusted bins
Target distance (m)	1.5	52	0.3257	18
Escape time (s)	0.1	5.4	0.0737	32
Escape distance (m)	1	36	0.3163	24
Minimum distance to path (m)	1.5	17	0.2244	26

Table B1. Parameters for bins of Ω.