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**Dennis M. Shaffer, Richard S. Marken,
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Chasin' choppers: using unpredictable trajectories to test theories of object interception

Dennis M. Shaffer · Richard S. Marken · Igor Dolgov · Andrew B. Maynor

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Abstract Three theories of the informational basis for object interception strategies were tested in an experiment where participants pursued toy helicopters. Helicopters were used as targets because their unpredictable trajectories have different effects on the optical variables that have been proposed as the basis of object interception, providing a basis for determining the variables that best explain this behavior. Participants pursued helicopters while the positions of both pursuer and helicopter were continuously monitored. Using models to predict the observed optical trajectories of the helicopter and ground positions of the pursuer, optical acceleration was eliminated as a basis of object interception. A model based on control of optical velocity (COV) provided the best match to pursuer ground movements, while one based on segments of linear optical trajectories (SLOT) provided the best match to the observed optical trajectories. We describe suggestions for further research to distinguish the COV and SLOT models.

Keywords Perception and Action · Navigation

Theories of object interception have proposed different control strategies for intercepting objects such as baseballs, cricket balls, Frisbees, and virtual soccer balls (Chapman, 1968; Dienes & McLeod, 1993; McBeath, Shaffer, & Kaiser, 1995, 1996; McLeod & Dienes, 1996; McLeod, Reed, & Dienes, 2001, 2003, 2006; McLeod, Reed, Gilson, & Glennerster,

2008; Michaels & Oudejans, 1992; Shaffer, McBeath, Krauchunas, & Sugar, 2008; Sugar & McBeath, 2001). Several strategies have been proposed as explanations of the interceptive behavior involving these different types of target objects: linear optical trajectory (LOT; McBeath et al., 1995), optical acceleration cancellation (OAC; Chapman, 1968), generalized OAC (GOAC; McLeod et al., 2006), segmented LOT (SLOT; Shaffer, Krauchunas, Eddy, & McBeath, 2004; Shaffer et al., 2008), and control of optical velocity (COV; Marken, 2001). These object interception strategies differ mainly in terms of the type of optical information that is assumed to be the basis of object interception. The aim of this research is to determine which of these different proposals regarding the informational basis of object interception provides the best explanation of this behavior.

The informational basis of object interception

The informational basis of target interception behavior refers to information in the retinal array about the actual position of the target object, relative to the pursuer. All proposals regarding the informational basis of object interception assume that this information is based on the vertical and lateral optical angles subtended by the target object in the visual field of the pursuer. One way to think about what is meant by optical angles is to imagine that we placed a camera on the head of a pursuer who looked directly at the target at each point in time and eventually intercepted the target. The vertical optical angle would be measured by the movement or tilt of the camera vertically at each point in time relative to the target, while the lateral optical angle would be measured by the movement or tilt of the camera laterally at each point in time relative to the target. Figure 1 shows that the vertical optical angle, α , is the visual angle subtended by the vertical distance from target to the horizon; the lateral optical angle, β , is the visual angle subtended by the horizontal distance between

D. M. Shaffer (✉) · A. B. Maynor
Department of Psychology, Ohio State University Mansfield,
1760 University Drive, Mansfield, OH 44906, USA
e-mail: shaffer.247@osu.edu

R. S. Marken
Department of Psychology, University of California,
Los Angeles, Los Angeles, CA, USA

I. Dolgov
Department of Psychology, New Mexico State University,
Las Cruces, NM, USA

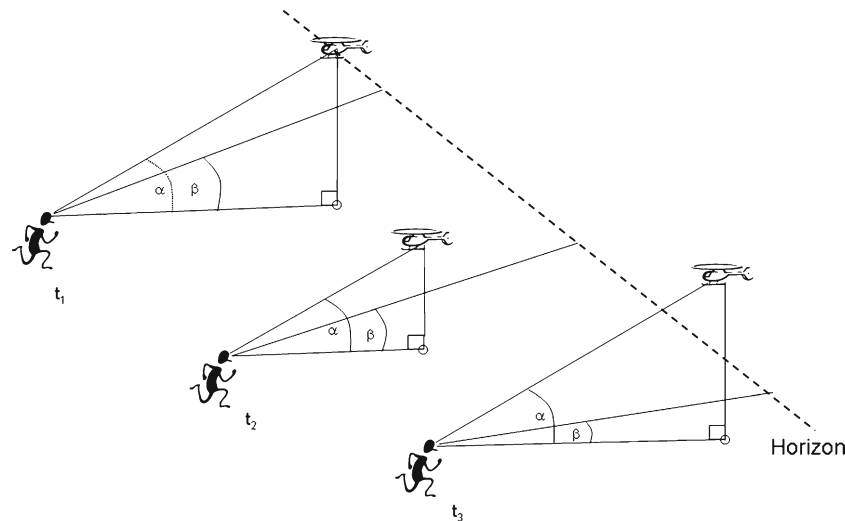


Fig. 1 Optical variables used by the model. Pursuer is shown moving laterally and forward in equal temporal intervals (t_1 – t_3) to intercept the target (helicopter). The vertical optical angle between the target and the horizon is α ; the lateral angle between the target and pursuer is β

target and pursuer. The different positions of the pursuer and target in the figure show that these optical angles vary over time depending on changes in the position of both the target object and the pursuer, simultaneously.

The LOT hypothesis assumes that pursuers move so as to keep the optical projection of the target object moving in a straight line, which is equivalent to keeping the ratio, Ψ , of changes in the object's lateral optical angle ($d\beta/dt$) to changes in its vertical optical angle ($d\alpha/dt$) constant (McBeath et al., 1995, 1996). This assumption is based on the observation that the temporal paths of the optical projection—the optical trajectory—of baseballs hit to outfielders (these trajectories having been recorded by a shoulder-mounted video camera during each catch) are nearly perfectly straight lines (McBeath et al., 1995). Thus, LOT assumes that the informational basis of object interception is the ratio $\Psi = (d\beta/dt)/(d\alpha/dt)$ and that interception is accomplished when the pursuer (such as a baseball outfielder) moves so as to keep Ψ constant, maintaining a linear optical trajectory of the target.

The OAC hypothesis assumes that pursuers move so as to keep the change in the velocity of the vertical optical angle, α , of the pursued object, which is the acceleration of α ($d^2\alpha/dt^2$), equal to zero. This hypothesis is based on an analysis by Chapman (1968), who showed that a fly ball hit directly toward a fielder will be intercepted if the fielder moves so as to keep the vertical optical acceleration of the ball ($d^2\alpha/dt^2$) equal to zero.

GOAC is a broader application of OAC that can handle the interception of objects that are not hit directly toward the pursuer. GOAC assumes that pursuers move so as to keep the vertical optical angle α increasing at a steadily decreasing rate (i.e., keep vertical optical velocity, or $d\alpha/dt$, decreasing), while keeping the velocity of the lateral optical angle, $d\beta/dt$,

constant. One way to keep the vertical optical angle α increasing at a steadily decreasing rate is to keep $d^2\alpha/dt^2$ equal to zero (i.e., maintain OAC). Thus, OAC is one way to achieve GOAC maintenance of the vertical optical angle α (McLeod et al., 2006).

The COV hypothesis is very similar to both of the OAC/GOAC hypotheses. COV differs from OAC only in that it assumes that the informational basis of object interception in the vertical direction is vertical optical velocity, $d\alpha/dt$, rather than vertical optical acceleration, $d^2\alpha/dt^2$, and, of course, in that COV has a lateral component to account for lateral optical movement. COV differs from GOAC, first, in that COV assumes that the pursuer will maintain constant vertical optical velocity, while GOAC assumes that the vertical optical velocity decreases. COV also differs from GOAC in that COV assumes that the informational basis for object interception in the lateral direction is the lateral optical angle, β , rather than lateral optical velocity, $d\beta/dt$, of the target. The COV model will be described in more detailed when we discuss the analysis of our research results.

Research testing object interception strategies

Research on object interception strategies is aimed at providing a basis for understanding the organization of all goal-oriented behavior. However, this research has yet to provide a conclusive answer to the question of how object interception behavior works. For example, LOT, OAC/GOAC, and COV have been shown to be consistent with the results of research on catching fly balls in baseball and cricket (McBeath et al., 1995, 1996; Marken, 2001; McLeod & Dienes, 1996; McLeod et al., 2003, 2006; Michaels & Oudejans, 1992; Shaffer &

McBeath, 2002; Shaffer et al., 2008); LOT, and OAC/GOAC have been shown to be consistent with the results of research on fielding ground balls in baseball (Sugar, McBeath, & Wang, 2006); SLOT and COV have been shown to be consistent with the results of research on dogs navigating to catch Frisbees (Marken, 2005; Shaffer et al., 2004); and LOT, OAC, and GOAC have been shown to be consistent with the results of research on robotic navigation for interception (Sugar & McBeath, 2001).

The fact that several different strategies appear to work equally well at explaining the same research results may result from the fact that these strategies are typically tested using objects moving in relatively predictable trajectories. Such trajectories confound the different optical variables that each model has proposed as the informational basis of object interception. For example, when a baseball travels in a relatively parabolic trajectory, optical acceleration and velocity are partially confounded, since velocity can be held constant at many different values when acceleration is zero. Marken (2005) has shown that it is possible to remove some of this confounding by introducing disturbances in the form of unpredictable midflight changes to object trajectories that differentially affect the optical variables proposed as the basis of object interception.

Research using midflight disturbances to object trajectories

The first studies of object interception that introduced such midflight disturbances were done by Shaffer et al. (2004) and then again by Shaffer et al. (2008). Results of trials in those studies where the object changed direction midflight were inconsistent with the LOT hypothesis; the observed optical trajectories of Frisbees, which make unpredictable midflight path changes, were not singular straight lines (Shaffer et al., 2004; Shaffer et al., 2008). This led to the development of the segmented version of LOT (SLOT), which assumes that pursuers maintain a linear optical trajectory of a particular slope until there is an abrupt change in the target's direction, at which point a new linear trajectory (segment) is maintained at a different slope. Both SLOT and OAC/GOAC were able to account for the optical trajectories observed for dogs chasing Frisbees (Shaffer et al., 2004), but only SLOT could account for the optical trajectories observed for humans chasing Frisbees (Shaffer et al., 2008).

Two other studies that experimentally manipulated object trajectories in midflight were done by Fink, Foo, and Warren (2009) and McLeod et al. (2008). McLeod et al. (2008) showed that GOAC was able to account for the optical trajectories observed for soccer ball interception ("headers"). They also found that the original, nonsegmented version of LOT could not explain these trajectories. However, the

apparent failure of LOT in this case was based on a qualitative evaluation of the nonlinearity of the entire optical trajectory, which did not appear to be segmented. The appearance of nonlinearity seems to have resulted from the fact that the optical trajectories included data that went up to the moment of interception, where the trajectory becomes quite irregular.¹

Fink et al. (2009) performed a virtual reality test of people chasing baseballs where the direction of the ball was changed in midflight. They concluded that the nonsegmented version of LOT could not explain the perturbed trajectories, while OAC (and thus, GOAC) could (Fink et al., 2009). However, researchers have pointed to several aspects of this study that seem to weaken these conclusions (Shaffer & McBeath, 2002; Shaffer et al., 2008; Shaffer, McBeath, Roy, & Krauchunas, 2003), not the least of which being that the version of LOT that failed was based on tangents, rather than the optical angles that are the actual basis of the LOT strategy (McBeath et al., 1996).

Aim of the present research

Two questions remain regarding studies of object interception involving the manipulation of midflight trajectories: (1) Could the experiments be improved through the use of less predictable trajectories (Marken, 2005), and (2) could the analyses be improved through the use of working models. The first question arises because the midflight perturbations used in some studies always occurred at the same time point within the target trajectory, making them quite predictable, especially over time (e.g., Fink et al., 2009; McLeod et al., 2008). The second arises because analysis of the results of these studies have typically been based on post hoc curve fitting where, for example, linear regression is used to fit straight lines to the observed optical trajectories (McBeath et al., 1995; McLeod et al., 2006, 2008; Shaffer et al., 2008). Fitting a working model to the results would provide a more rigorous test of theories of object interception, because it requires proposing a mechanism that produces behavior like that of the actual pursuer based on the assumed informational basis of that behavior.

The aim of the present research is to address these two questions by having pursuers try to intercept objects

¹ Previous work has excluded the last 0.5 s of the optical trajectory, since other cues become available and are presumably used as primary cues during the final phase of interception (McLeod et al., 2006; Regan, 1997; Regan & Gray, 2001). Therefore, the last 0.5 s of an interception is considered a separate phase. However, we have shown that for unusually high baseball trajectories, even when the final phase is not removed, the LOT is maintained within one standard deviation of optical ball size up until the moment the ball is caught and that this increase in optical ball size leads to different optical trajectories, depending on whether linearity is being maintained for the center of the ball or for an edge (Shaffer et al., 2008).

that unpredictably change trajectory several times in midflight and to compare the observed behavior of the pursuers with the corresponding behavior of working models of object interception.

Method

Participants

Three males experienced at pursuing and catching moving targets in the context of playing team sports participated in the experiment.

Design and procedure

We conducted this study in an indoor gymnasium. A Vicon eight-camera motion capture system with millimeter accuracy recorded pursuer head position and helicopter position at 60 Hz. Reflective tape was placed at the center of a bicycle helmet that the pursuer wore. The cameras localized the reflective tape at the center of the helmet, and we used this as the x -, y -, z -coordinate of the pursuer. Similarly, we placed reflective tape on the pod of the helicopter. The cameras localized this, and we used this as the x -, y -, z -coordinate of the helicopter. Raw motion capture data were rendered using ViconIQ software, and then the reflective markers on the pod of the helicopter and at the center of the helmet on participants' heads were labeled using Vicon BodyBuilder software. The data were then further processed in ViconIQ software in order to fill trajectory gaps 0.5 s in duration or smaller, using a spline algorithm built into ViconIQ (such gaps occurred in instances in which the marker was occluded from the cameras). The resulting trajectories, which consist of 3-D marker positions, were exported to a text file and used for computing the relative angles for our study.

We estimated the time-varying values of the optical angles α and β on a given trial by measuring at each instant in time the location of the helicopter and the location of the pursuer's head. Then we took α to be the angle subtended at the pursuer's head and extending to the reflective marker on the helicopter at two adjacent instances in time in the vertical (or y -coordinate) direction. We took β to be the angle subtended at the pursuer's head and extending out to the reflective marker on the helicopter at two adjacent instances in time in the lateral (or x -coordinate) direction.

The pursuer started 5 m from directly in front of the toy helicopter. Pursuers were instructed to chase the toy helicopter and catch it before it hit the ground. The person controlling the toy helicopter (the "controller") stood behind the pursuer so he could not be seen by the pursuer. The controller was instructed to make the toy helicopter change directions

several times throughout its flight. These changes were made according to the controllers' discretion and were not manipulated at specific times or places. The controller made the toy helicopter perform a variety of maneuvers so as to manipulate the course and speed of the pursuer several times throughout the helicopter's flight.

Results

There were a total of 50 trials. On 6 trials, either the helicopter was not intercepted by the pursuer (2), or the data were not codable due to interference with the signal from the cameras (4). On 3 trials, the pursuer did not move for at least one half of the trial due to the helicopter making only small movements or hovering essentially in the same place. This was typically due to signal interference between the remote control and the toy helicopter. Thus, we analyzed data from 41 trials. We derived the optical coordinates of the helicopter from the angle between the x -, y -, and z -coordinates of the pursuer and helicopter. The variation in these optical coordinates during a trial is the optical trajectory traced out by the helicopter; the variation in the ground coordinates of the pursuer during a trial is the ground path traced out by the pursuer. We analyzed the optical trajectory and ground path data until the last 0.5 s of each trial, where it has been shown that other cues are used for interception (Regan, 1997; Regan & Gray, 2001).

Comparing observed and predicted optical trajectories for SLOT, OAC, and GOAC

We compared the OAC, GOAC, and SLOT models in terms of their ability to account for the observed optical trajectories. LOT was not included in this comparison because the observer optical trajectories were clearly nonlinear. The comparison was done using the same methods that had been employed in earlier comparisons of these models (e.g., Fink et al., 2009; McLeod et al., 2008; Shaffer et al., 2008). Our aim was to see whether the use of objects with highly unpredictable trajectories (the helicopter) would allow a clearer distinction between these models.

In order to perform this analysis, we calculated optical trajectories in terms of the vertical and lateral optical angles based on the observed trajectories of the helicopter and movements of the pursuer on each trial. To evaluate OAC, we plotted $\tan\alpha$ versus time. The results of this analysis showed that, averaging over 41 trials, OAC accounted for 64.58 % of the variance in observed optical trajectories ($SD = 32$ %, range = 96.7 %). Representative trials are shown in Fig. 2. This figure shows that OAC typically fails to account for a significant proportion of the variance in $\tan\alpha$. OAC failed for one of two reasons: Either (1) $\tan\alpha$ decreased, as it did in the top two panels, or (2) α came close to and, in some cases (as in the

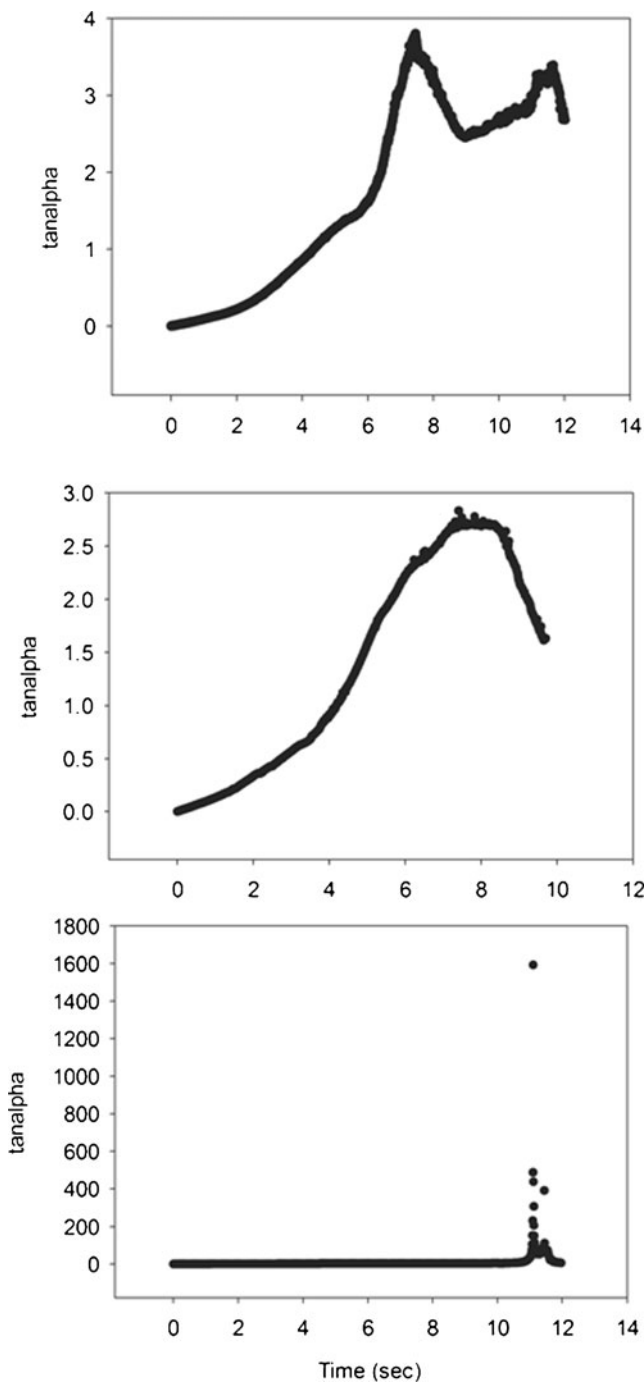


Fig. 2 Representative plots of $\tan\alpha$ versus time. Best-fit lines accounted for 25.4 %, 41.27 %, and 29.62 % of the variance in the optical trajectory in the panels from top to bottom, respectively

bottom panel), actually reached 90° , at which point the pursuer is looking virtually directly over their head at the helicopter and the tangent function runs to positive infinity.

In order to analyze the vertical component of GOAC, we first applied regression lines to plots of the velocity of the vertical optical angle, $d\alpha/dt$, against time. We then calculated the correlation coefficient, identified whether it was

positive or negative, and tested to see whether it was statistically significant. Since a plot can look relatively constant but can still be significantly increasing or decreasing statistically, and to fairly assess “constancy,” we also adopted a criterion where the magnitude of the correlation coefficient had to be at least $r = .30$ to be considered “significantly” increasing or decreasing. This corresponds to $R^2 = .09$, which is considered a moderate effect size (Cohen, 1988). If $d\alpha/dt$ decreased according to our criterion, it would be evidence in favor of GOAC.

Analysis of $d\alpha/dt$ against time revealed that $d\alpha/dt$ was maintained as constant (24 trials) or significantly increasing (1 trial) as often as it was maintained as significantly decreasing (16 trials), $\chi^2(1) = 1.2$, $p > .1$. Representative plots of $d\alpha/dt$ versus time are shown in the left panels of Fig. 3. The top left panel shows $d\alpha/dt$ significantly decreasing, while the bottom two panels show $d\alpha/dt$ staying constant, as it did for the majority of trials. The bottom two panels serve as examples of how GOAC failed to explain the vertical component of the optical trajectory.

We used the same strategy for analyzing the lateral component of GOAC, $d\beta/dt$, as we did for analyzing the vertical component, except that, here, we graphed the lateral optical angle versus time. If $d\beta/dt$ was maintained as constant according to our criterion, it would be evidence in favor of GOAC. Analysis of $d\beta/dt$ against time revealed that $d\beta/dt$ was maintained as constant (37 trials) significantly more than it was maintained as significantly increasing (3 trials) or decreasing (1 trial), $\chi^2(1) = 26.56$, $p < .005$. Representative plots of $d\beta/dt$ versus time are shown in the right panels of Fig. 3.

To evaluate SLOT, we used regression analysis to determine how much of the variance in the observed optical trajectories could be accounted for by a set of optimally oriented linear segments.² The SLOT accounted for a mean of 95.1 % of the variance ($SD = 2.4$ %, $R = 9.1$ %). Representative plots of SLOT—the lateral optical angle plotted against the vertical optical angle—are shown in Fig. 4. The graphed trials are the same as those in Fig. 2.

A paired-samples t -test was performed on the variance accounted for by OAC and SLOT strategies (no such comparisons could be made for GOAC, since R^2 s were not part of the analysis). SLOT accounted for significantly more variance than did OAC, $t(40) = 6.14$, $p < .001$. This was a large effect, $R^2 = .49$. We also tested the variability (coefficient of variation, or CV) of both OAC and LOT as a measure of reliability and found that the OAC was almost 20 times as variable in explaining interceptive behavior as was a SLOT ($CV_{OAC} = 49.55$; $CV_{SLOT} = 2.52$).

² SLOT segments were identified by having someone blind to the hypotheses of the experiment identify inflection points (obvious changes in direction) in the observed optical trajectories. It was possible to identify inflections to within 1/60th of a second of where the inflection occurred. The number of inflections identified in the observed trajectories ranged from 2 to 11, with a median of 6 ($M = 5.71$, $SD = 2.07$).

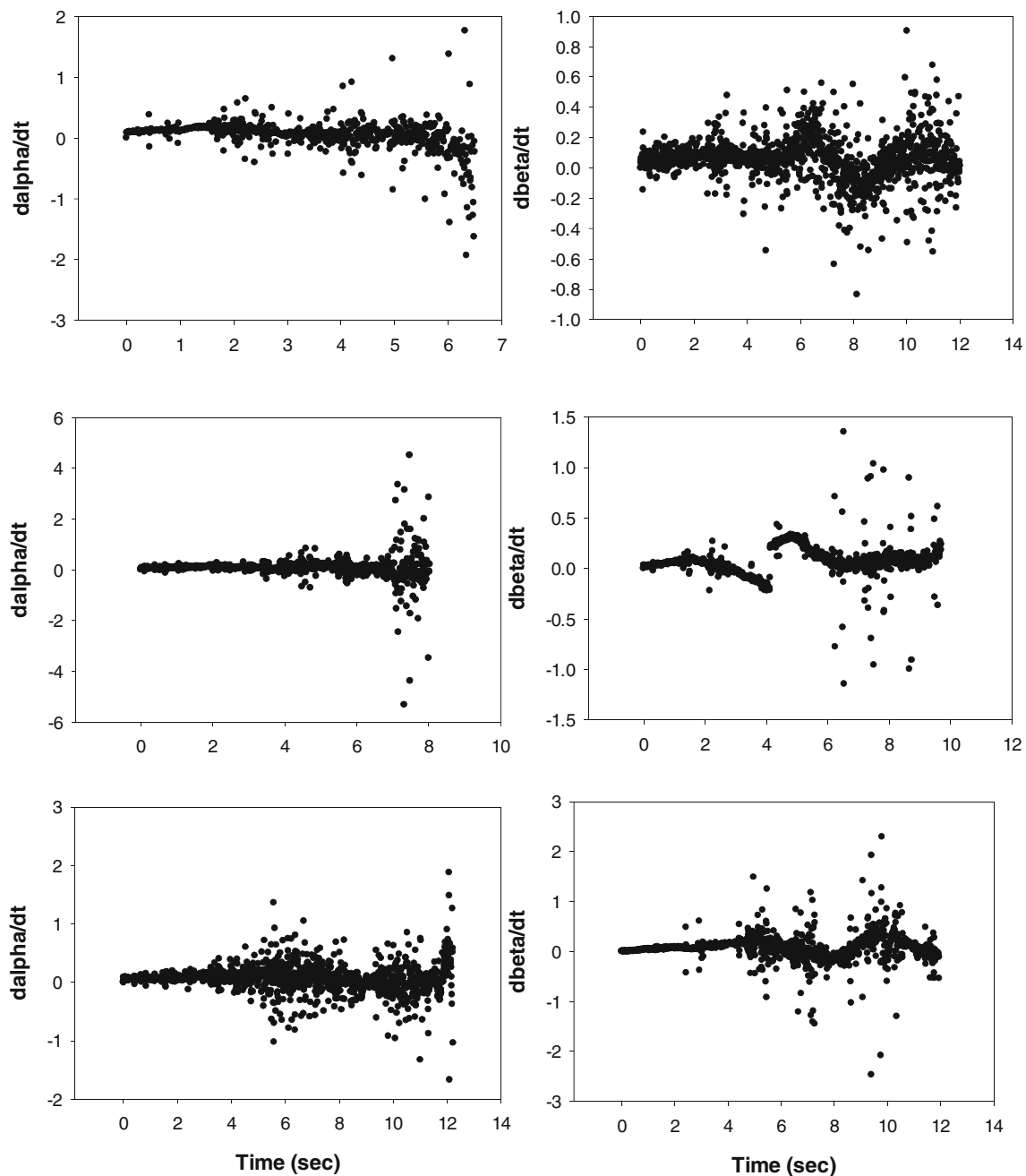


Fig. 3 Representative plots of $d\alpha/dt$ against time and $d\beta/dt$ against time. Left panels: $d\alpha/dt$ is plotted against time. In the top panel, $d\alpha/dt$ significantly decreases, while in the bottom two panels, $d\alpha/dt$ remains

constant. Right panels: $d\beta/dt$ is plotted against time. In the top panel, $d\beta/dt$ significantly decreases, while in the lower two, $d\beta/dt$ stays constant

Testing working models of object interception—COV and GOAC

We compared both the observed optical trajectories and pursuer's ground paths with those produced by a working model of object interception. It was a "working" model in the sense that it was implemented as a computer program that produced object

interception behavior (two-dimensional ground tracks) on the basis of the actual helicopter paths (temporal variations in the x -, y -, z -coordinates of the helicopter) observed in the experiment. The coordinates of the running space were rotated and translated so that, on each trial, the model pursuer was at the origin of the x - and y -axes that defined this space and the helicopter launch point was mapped to the 0 position of the x -axis.

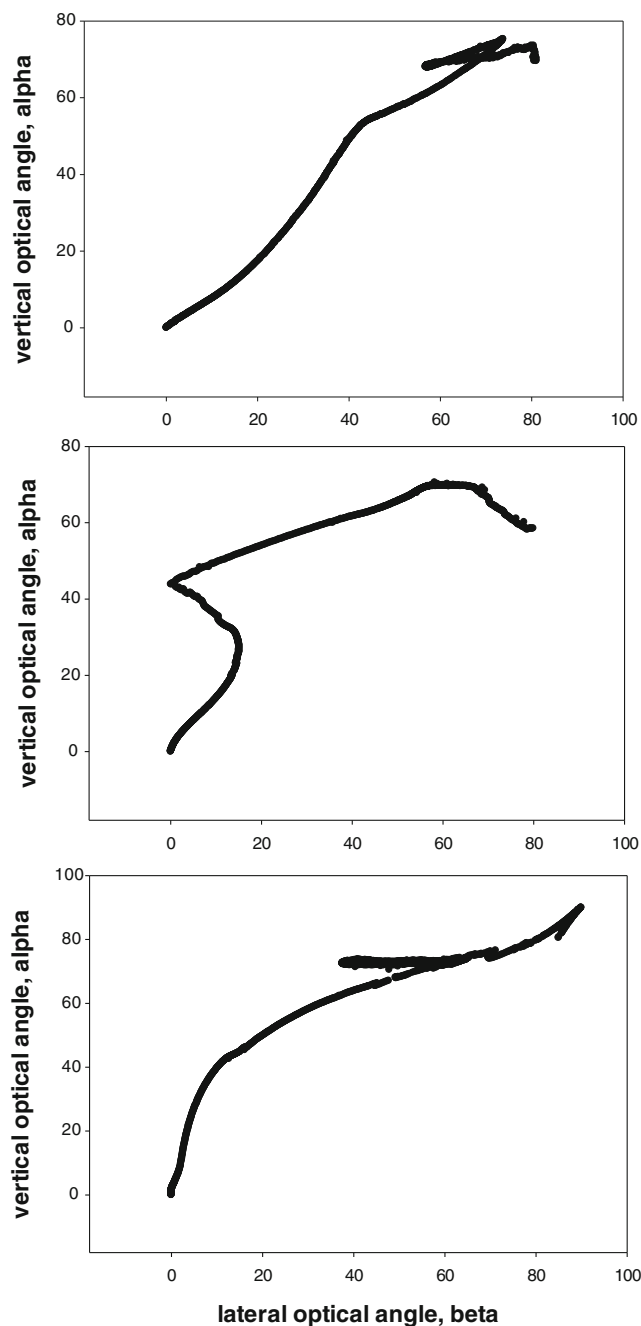


Fig. 4 Representative plots of α versus β for SLOTT, which correspond to the same trials, top to bottom, as those shown in Fig. 2, are shown. Approximations to best-fit lines for each trajectory portion are shown. Best-fit lines accounted for 97.96 %, 97.55 %, and 96.05 % of the variance in the optical trajectory in the panels from top to bottom, respectively

We tested two versions of the model that differed in terms of the optical information that was the basis for the object interception behavior. One version implemented the COV model. It used the vertical optical velocity, $d\alpha/dt$, and lateral optical angle, β , of the target as the basis of object interception

behavior. The other version of the model, which is equivalent to the GOAC model specifically by using OAC in the vertical direction, rather than more generally using decreasing vertical optical velocity, used vertical optical acceleration, $d^2\alpha/dt^2$, and lateral optical velocity, $d\beta/dt$, as the basis of interception. So the only difference between the two working models was in the informational basis of the object interception behavior produced by the models.

The COV model

The COV version of the model is shown in Fig. 5. The model consists of two control systems, one controlling the vertical optical velocity ($d\alpha/dt$) of the pursued object (the helicopter) by producing outputs, o_x , that move the pursuer forward or backward in the x -dimension and the other controlling the lateral optical angle, β , of the helicopter by producing outputs, o_y , that move the pursuer laterally in the y -dimension. This is a closed-loop control model of object interception behavior. The horizontal line running through the middle of the figure separates the two control systems that pursue the helicopter from the environment that contains the moving helicopter.

The variables controlled by each control system, $d\alpha/dt$ and β , are perceptions computed as a function of temporal variations in the observed position—changes in the x -, y -, z -coordinates over time—of the helicopter. The neural networks that compute these perceptions are represented by the boxes labeled $p_v = d\alpha/dt$ and $p_l = \beta$. The perceptions, p_v and p_l , are compared, via subtraction, to reference signals (r_v and r_l , respectively) that specify the goal values for these perceptions. The difference between each perception and its reference signal is an error signal, e , that drives the model outputs o_x and o_y .

The movement of the pursuer relative to the object pursued has immediate feedback effects on the vertical and lateral optical angles, q_α and q_β , of the pursued object relative to the pursuer. These feedback effects are indicated in Fig. 5 by the arrows connecting the pursuer's outputs, o_x and o_y , to the optical angles q_α and q_β . The optical angles are the inputs to the perceptual functions that compute the perceptual variables, p_v and p_l , that are under control.

Note that each output in Fig. 5 has feedback effects on both optical angles. This does not create a conflict between the systems, because the effect of an output, such as o_x , on the optical variable that it is not controlling, q_β in this case, is simply treated as a disturbance that is opposed by the output, o_y , of the system that is controlling q_β . Thus, there is no conflict between the two control systems.³

³ The details of the computer simulation of COV can be provided upon request.

COV Model

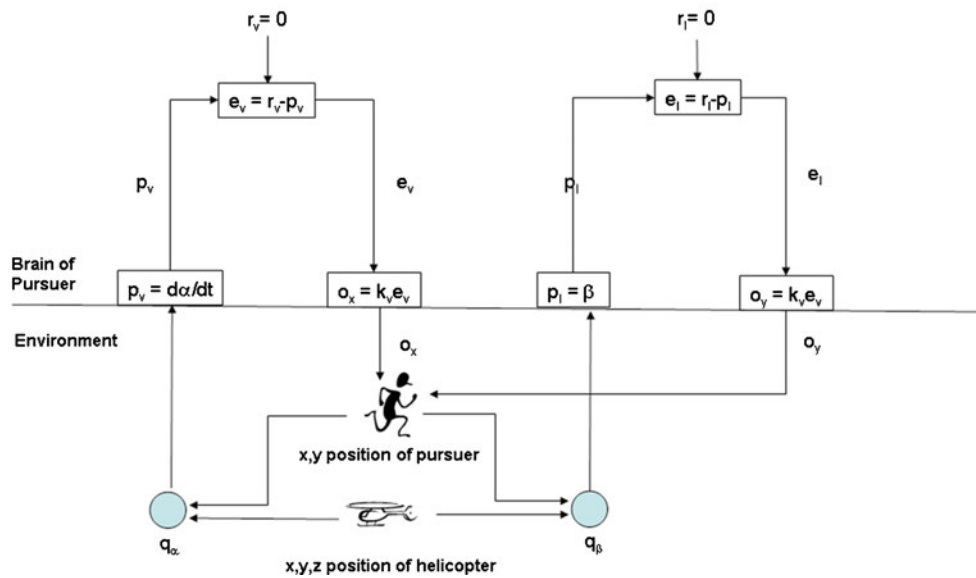


Fig. 5 The control systems that make up the control of optical velocity (COV) model of object interception. The system on the left controls vertical optical velocity ($d\alpha/dt$) by moving the pursuer forward and

back (in the x -dimension); the system on the right controls lateral angle (β) by moving the pursuer laterally (in the y -dimension)

The GOAC model

The GOAC version of the model differs from COV only in the assumption that one basis of object interception is vertical optical acceleration, $d^2\alpha/dt$, rather than vertical optical velocity, $d\alpha/dt$, and that the other is lateral optical velocity, $d\beta/dt$, rather than lateral optical angle, β .

Analysis of ground tracks for COV and GOAC

We compared the working version of GOAC and COV in terms of their ability to account for the observed variance in the two-dimensional ground tracks of pursuers that were observed on each trial of the experiment. The SLOT model was not included in this analysis because there is currently no working version of the model that can act—by moving appropriately on the ground—so as to change the slope of the linear segments of optical trajectory appropriately.

We used regression analysis to determine how much of the variance in the observed ground tracks was accounted for by the ground tracks produced by the best-fitting GOAC and COV models. The results of this analysis showed that, averaging over 41 trials, the GOAC model accounted for an average of 75 % of the variance in observed ground tracks ($SD = 26\%$, $R = 99\%$), while the COV model accounted for a mean of 93 % of the variance ($SD = 6\%$, $R = 27\%$). The fit of the COV model to the ground tracks on four experimental trials (“Takes”) is shown in Fig. 6.

A paired-samples t -test revealed that COV accounts for significantly more variance in the ground tracks than does GOAC, $t(40) = 4.77$, $p < .001$. This was a large effect, $R^2 = .36$. We also tested the variability of both GOAC and COV as a measure of reliability and found that the GOAC was more than 5 times as variable in explaining interceptive behavior as was COV ($CV_{OAC} = 34.67$, $CV_{COV} = 6.45$).

The relative success of the two models can also be measured in terms of RMS deviation of model behavior from observed ground tracks. Again averaging over 41 trials, the RMS deviation of the GOAC model from observed ground tracks was 30.18 cm ($SD = 19.02$ cm), and the RMS deviation of the COV model from observed ground tracks was 16.51 cm ($SD = 10.61$ cm). A paired-samples t -test revealed that COV had far less error in predicting ground tracks than did GOAC, $t(40) = -5.39$, $p < .001$. This was also a large effect, $R^2 = .42$. So, the COV model was almost twice as accurate as the GOAC model at predicting the ground tracks that controlled the respective types of optical information during pursuit.

It should be noted that the fit of both the COV and OAC/GOAC versions of the model was obtained by estimating only four free parameters (the gain and slowing factors for the output functions of the two control systems). Thus, the superiority of the COV version of the model in terms of accounting for the observed ground tracks can be attributed only to the fact that the informational basis of the behavior of this model differed from that of the OAC/GOAC version.

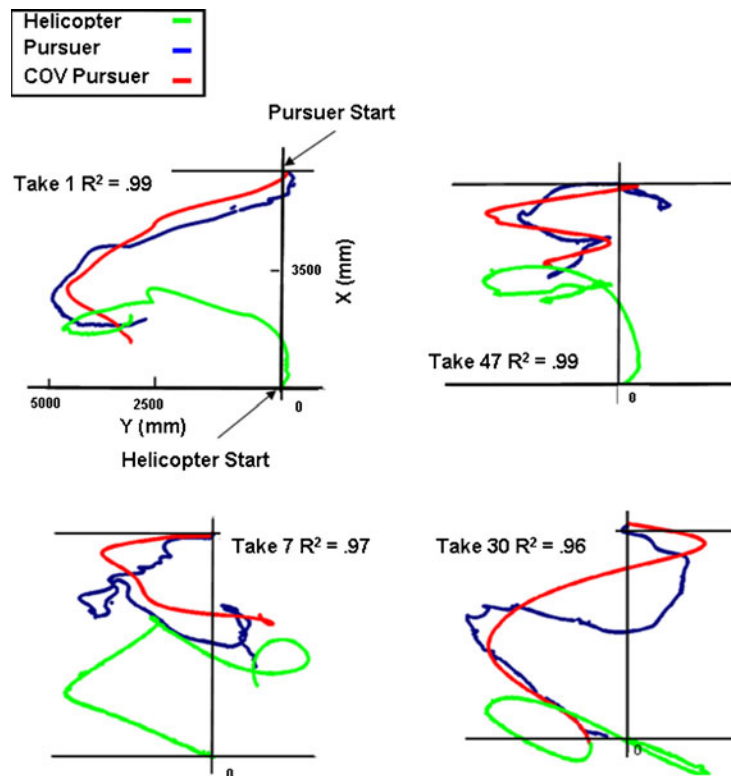


Fig. 6 Some representative results of the COV simulation of pursuer ground tracks. The plots show a two-dimensional bird's-eye view of helicopter position (green line), actual pursuer position (blue line), and the COV model pursuer position (red line) over the course of four

different trials ("Takes"). Note that on all trials, the COV pursuer moves to intercept the helicopter (which moves in a very erratic path) in nearly the same way as the actual pursuer

Analysis of optical trajectories for COV and GOAC

It was also possible to compare the optical trajectories of α and β produced by the working versions of the COV and GOAC models with those observed in the experiment. The fit of model to actual trajectories was measured in terms of R^2 , which is the proportion of variance in the observed values of α and β accounted for by the corresponding values of α and β produced by the model. The average R^2 was calculated for 41 experimental trials. The COV model accounted for 84 % ($SD = 13$ %), while the GOAC model accounted for 75 % ($SD = 15$ %) of the variance in the optical trajectories. A paired-samples t -test revealed that COV accounts for significantly more variance in the optical trajectories than does GOAC, $t(40) = 4.44$, $p < .001$. Nevertheless, the COV model accounted for considerable less variance in the optical trajectories (84 %) than did the SLOT model (95.1 %).

The comparison of the ability of the SLOT and COV models to account for the optical trajectory data is complicated by the fact that the models differed in terms of the number of free parameters used to make these predictions. The COV model used four free parameters to estimate the optical trajectories on all trials. The SLOT model uses two free parameters (slope, intercept) for each linear segment fit

to the observed optical trajectory; thus, the number of free parameters used to account for the data depends on the number of segments found in each trajectory.

Discussion

We have shown that the behavior of people pursuing a toy helicopter that changes direction unpredictably during its flight is best accounted for by the COV and SLOT models. The SLOT model did best at accounting for the variance in the optical trajectories observed during each pursuit, accounting for over 95 % of the variance in these trajectories. The COV did best at accounting for the ground tracks of the pursuers accounting for an average of 93 % of the variance in these tracks. The use of targets that follow highly unpredictable trajectories made it possible to discriminate the OAC/GOAC and COV models of pursuer ground tracks. Although vertical optical acceleration and velocity are somewhat confounded, there were many trials where these two variables behaved quite differently due to the irregularity of the helicopter trajectories. This made it possible to show that a model that controls optical velocity acts much more like the actual pursuer than does one that controls optical acceleration. Also, as

far as we are aware, this is the first test of the ability of a model that controls different types of optical information to account for the ground tracks—the behavior of the pursuer—observed in an object interception task. The model made it possible to determine that vertical optical velocity, $d\alpha/dt$, and lateral angle, β , as per COV, are better approximations to the informational basis of object interception than vertical optical acceleration, $d^2\alpha/dt^2$, and lateral optical velocity, $d\beta/dt$, as per OAC/GOAC. Clearly, this is an important advance in our understanding of the informational basis of goal-oriented behavior.

Comparing COV and SLOT

In order to discriminate between the two successful models of object interception found in this research—SLOT and COV—it will be necessary to design a working version of the SLOT model to see whether it can do as well at accounting for the variation in the ground tracks of the pursuers as did the COV model. While the SLOT model did better than the COV model in accounting for optical trajectories, the COV model still did fairly well, while also accounting for most of the variability on the ground tracks (93 %).

The COV strategy is more parsimonious than SLOT because the pursuer simply needs to keep optical velocity at or near zero to maintain a COV, whereas as many as 11 perturbations had to be accounted for with a SLOT in a given trial in the present study. However, parsimony is only one, and not necessarily the main, consideration when comparing explanations of behavior. Another consideration is adaptive significance across species.

Adaptive behavior consistent with maintaining spatiotemporal constancy between a pursuer and a moving target, which is characteristic of the SLOT heuristic, has been observed in many species. Predator–prey characteristics of bats, birds, tethered flies, houseflies, and dragonflies are also consistent with maintaining optical angle constancy between themselves and their prey during inflight pursuit (Jablonski, 1999; Kuc, 1994; Masters, Moffat, & Simmons, 1985; Simmons, Fenton, & O'Farrell, 1979; Simmons & Kick, 1983; Olberg, Worthington, & Venator, 2000). Thus, a strategy that changes reference values with perturbations in the movement of prey is evolutionarily advantageous. In these scenarios, maintaining lateral movement at about zero will guarantee interception. While this could be a useful lateral strategy—to basically fly directly behind the target—it does not have empirical support and also requires that the animal is fast enough to close the depth (and perhaps height) gap between themselves and their target.

Humans probably developed interceptive abilities consistent with a COV and/or SLOT strategy that are viewer based, are independent of the movement of a target, allow the pursuer to make instantaneous changes in speed and

direction before interception occurs, are not tied to the target origin, and are independent of the relative positioning of the locomotor axis of the pursuer with regard to the target/target origin. This makes both these strategies appealing as universal tracking heuristics that may have evolved from interceptive strategies used in other domains and by other species.

Author Note Dennis M. Shaffer and Andrew Maynor, Department of Psychology, Ohio State University; Richard Marken, Department of Psychology, University of California, Los Angeles; Igor Dolgov, Department of Psychology, New Mexico State University. We would like to thank Ciara Adamovich and Ryan Withey for help in collecting and coding data. Correspondence concerning this article should be addressed to Dennis M. Shaffer, Department of Psychology, The Ohio State University–Mansfield, 1760 University Drive, Mansfield, OH 44906. E-mail: Shaffer.247@osu.edu

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