How do People Steer a Car to Intercept a Moving Target: Interceptions in Different Environments Point to One Strategy

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Title:

How do People Steer a Car to Intercept a Moving Target:

Interceptions in Different Environments Point to One Strategy

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Abstract

Which strategy people use to guide locomotor interception remains unclear despite considerable research and the importance of an answer with ramification into the heuristics and biases debate. Because the constant bearing (CB) strategy corresponds to the target-heading (CTH) strategy with an additional constraint, these two strategies can be confounded experimentally. But, the two strategies are distinct in the information they require: while the CTH strategy only requires access to the relative angle between the direction of motion and the target, the CB strategy requires access to a stable allocentric reference frame. Here, we manipulated the visual information about allocentric reference frames in three virtual environments and asked participants to steer a car to intercept a moving target. Participants' interception paths showed different degrees of curvature and their target-heading angles were approximately constant, consistent with the CTH strategy. By contrast, the target's bearing angle continuously changed in all participants except one. This particular participant produced linear interception paths with little change in the target's bearing angle, seemingly consistent with both strategies. This participant continued this pattern of steering even in the environment without any visual information about allocentric reference frames. Therefore, this pattern of steering is attributed to the CTH strategy rather than the CB strategy. The overall results add important evidence for the conclusion that locomotor interception is better accounted for by the CTH strategy and that experimentally observing a straight interception trajectory with a constant bearing angle is not sufficient evidence for the CB strategy.

Keywords: locomotor interception, constant target-heading strategy, constant bearing strategy, action control, vehicle steering

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Introduction

Locomotor interception of a moving target is widely performed by animals and humans, such as animal predators chasing their fleeing prey (Olberg, Worthington, & Venator, 2000; Lanchester & Mark, 1975; Ghose, Horiuchi, Krishnaprasad, & Moss, 2006) and fielders catching a fly ball in baseball (e.g. Chapman, 1968; McBeath, Shaffer, & Kaiser, 1995; Mcleod & Dienes, 1996). The importance of clarifying the nature of this interception strategy extends well beyond the understanding of visuomotor behavior, as it has been interpreted as a form of fast and frugal heuristic (Gigerenzer, 2001). Human actors perform interception using different end-effectors, such as sailors steering their ship to catch another moving vessel at sea and policemen driving a car to intercept a moving target in an open field. By asking participants to steer a car to intercept a moving target in a virtual environment, it has been shown recently that interceptive steering is consistent with the constant target-heading (CTH) strategy, i.e., during interception the target is maintained at a constant angle relative to the current heading direction (Zhao, Straub, & Rothkopf, 2019). However, as participants in that study performed interception in a virtual environment, which provided only limited visual information about allocentric reference frames, the question arises, whether the CTH strategy or other interception strategies are used in different environments. Therefore, in the current study, we manipulated the visual information about allocentric reference frames in three different virtual environments and examined whether participants would change their strategy depending on the availability of an allocentric reference frame.

Locomotor Interception Strategies and the Information Involved

Two strategies have been proposed to explain the guidance of locomotor interception (see Figure 1), both of which are consistent with the online approach to the visual control of action

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(see Zhao & Warren, 2015, Zhao & Warren, 2017; also see Zago, McIntyre, Senot, & Lacquaniti, 2009). If actors use the CTH strategy to guide locomotor interception, the target is kept at a constant angle relative to the current heading direction, i.e., the target-heading angle is constant. Since the strategy itself does not specify any particular constant value for the target-heading angle, different values can lead to different interception paths, from curved to linear trajectories. Accordingly, the information about the heading direction plays an important role in the CTH strategy. The heading direction could be determined from optic flow in the environment (Bruggeman, Zosh, & Warren, 2007; Li & Cheng, 2011, 2013; Warren, Kay, Zosh, Duchon, & Sahuc, 2001) or from the actor's egocentric axis (Harris & Bonas, 2002; Rushton, Harris, Lloyd, & Wann, 1998). Specifically, in the task of steering a car to intercept a moving target used here, the front of the car is always pointing in the current heading direction.

--- Insert Figure 1 about here ---

If actors instead use the constant bearing (CB) strategy, the target is kept at a constant angle relative to an allocentric reference axis, i.e., the target's bearing angle is constant. This constraint is sufficient to result in linear interception paths, if the velocities of both the actor and the target are constant. Importantly the CB strategy therefore requires access to a stable allocentric reference frame. Allocentric reference frames could be provided visually by a stationary background or landmarks, such as a wall in a room or buildings in an open field. Even when such visual information is absent, people can maintain an allocentric reference frame through podokinetic and vestibular information during walking (see Loomis, DaSilva, Fujita, & Fukusima, 1992; Philbeck, Loomis, & Beall, 1997). In the present task of steering a car,

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however, the proprioceptive information from maneuvers of the steering wheel alone is not sufficient to accurately maintain a stable allocentric reference frame (Wallis, Chatziastros, & Bülthoff, 2002; Wallis, Chatziastros, Tresilian, & Tomasevic, 2007).

Locomotor Interception Strategies in Steering Interception Tasks

Only few studies have examined the locomotor interception strategy in steering interception tasks. When participants walked to intercept a slow target (at about 1°/s at the beginning of a trial) in Rushton, Harris, Lloyd, and Wann (1998), they walked directly toward the target's current location maintaining the target-heading angle close to zero, which is consistent with the CTH strategy. However, when participants walked to intercept a faster target (at about 8°/s at the beginning of a trial) in Fajen and Warren (2004), their interceptions did not consistently support any particular interception strategy. Their interception paths were curved for some of the target movement paths, which is not consistent with the CB strategy but the target-heading angle continuously changed during interception for some of the target movement paths, which is not consistent with the CTH strategy.

In Zhao et al. (2019), we asked participants to steer a car to intercept a target which moved at 4.0, 5.0, or 6.0 m/s in a virtual environment. Participants steered curved interception paths and maintained the target-heading angle at an approximately constant value, and the target's bearing angle continuously changed during interception. These results therefore consistently support the CTH strategy. In that study, however, only one virtual environment which provided limited visual information about allocentric reference frames was used. This leads to the question whether the consistent support for the CTH strategy was a consequence of the amount of available information about a stable allocentric frame of reference.

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The Current Study

In the current study, we manipulated the visual information about allocentric reference frames in different virtual environments and examined whether participants would use the same interception strategy or different ones in different environments. Therefore, we created three virtual environments (see Figure 2). The textured-ground environment resembled a natural open field including distant landmarks providing optic flow and visual information about allocentric reference frames (Figure 2a). However, there was no obvious allocentric reference axis present. The plant-wall environment was identical to the textured-ground environment, but additionally contained a set of plants on the ground plane and a textured wall parallel to the target's path (Figure 2b). Thus, this environment provided richer visual information about allocentric reference frames including a clearly visible allocentric reference axis as well as richer optic flow. Finally, the green-ground environment consisted of only a gray sky and a ground plane of solid green, providing neither optic flow nor visual information about allocentric reference frames (Figure 2c). In this environment, the CTH strategy can be used to guide interception, but the CB strategy cannot be used, as it inherently needs access to an allocentric reference frame. Thus, even if actors produce linear interception paths with a constant bearing angle in this environment, this pattern of steering should not be attributed to the CB strategy. Instead, it should be attributed to the CTH strategy.

--- Insert Figure 2 about here ---

As participants performed locomotor interceptions in the textured-ground and plant-wall environments in Experiment 1, most of them produced curved interception paths with little

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change in the target-heading angle, consistent with the CTH strategy. However, one participant produced linear interception paths with little change in the target's bearing angle, seemingly consistent with the CTH strategy as well as the CB strategy. To clarify whether the observed trajectories were all attributable to the CTH strategy, we asked this particular participant and some new participants in Experiment 2 to perform the same virtual steering task in the plant-wall and the green-ground environments.

Experiment 1

We examined which strategy participants used to guide interception in the textured-ground environment and the plant-wall environment. In these environments, both the CTH and the CB strategy can be used concerning their required visual information. Moreover, the plant-wall environment provided richer visual information about allocentric reference frames including a clearly visible allocentric reference axis, as well as richer optic flow. We examined which strategy participants used to guide interception and whether they used different strategies in different environments.

Methods

Participants.

Twelve students at the Technical University of Darmstadt participated in this experiment (six women, six men; M_{age} = 24.5 years, SD_{age} = 7.6 years). They all had a driver's license for at least two years and had normal or corrected-to-normal vision. They read and signed a consent form before the experiment and received participation credit from the Institute of Psychology after the experiment.

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Apparatus.

We used the same apparatus as in Zhao et al. (2019). Participants sat in a chair and steered a force feedback steering wheel (Driving Force GT, Logitech, Newark, CA, US) fixed to a desk in front of the chair. We used Vizard software (WorldViz, Santa Barbara, CA, US) to generate all the virtual environments on a gaming PC. The display was presented in a head-mounted display (HMD, Oculus Rift DK 2, OculusVR, Irvine, CA, US) at 60 Hz, which provided stereoscopic viewing with an 80° (vertical) × 80° (horizontal) field of view. The distance between the two lenses of the HMD was fixed; we also fixed the interpupillary distance in Vizard at its default value (0.06 m). The steering wheel had a turning range of 450° left/right, its current turning angle determined the car's current turning rate with a proportion at 5°:1°/s. The car's heading was updated by integrating the turning rate of the car in each frame:

$$\varphi_{i+1} = \varphi_i + \Delta t_i \dot{\varphi}_i \qquad (1)$$

where φ_i is the heading direction in the ith frame, $\dot{\varphi}_i$ is the turning rate, and Δt_i is the duration of that frame, respectively. The car's location was updated by translating it in its current heading direction at a fixed speed of 7 m/s. In addition, we adjusted the setup so that participants' steering of the virtual car was much like their steering of a real car.

Display.

The textured-ground environment consisted of a round ground plane with a radius of 300 m, a blue sky with clouds, and a surrounding background image at the edge of the ground plane (Figure 2a). The ground plane was mapped with a random noise texture. The plant-wall environment was the textured-ground environment plus a textured wall and 210 plants on the ground (Figure 2b). To specify the locations of the objects in the environments, we set the center of the ground plane as the origin of the environments (x = 0, z = 0 m). The wall was 1000-m

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long, 12.5-m tall and parallel to the target path at a distance of 46-m. All plants were 0.6 m wide and 0.6 m in depth, with a random height from 0.4 to 0.8 m. They spanned from 0 to 90 m in z direction, distributed randomly in 10 rows, with 5 to 13 m between rows and 3.6 to 9.6 m between two plants in a row. To prevent the persistent influence of landmarks across trials on interception, the surrounding background image and the sky/clouds were rotated randomly by an angle from 0° to 270° about the origin of the environments before each trial. In addition, in the plant-wall environment, the layout of the plants was randomly rotated by an angle from -10° to 10° about the origin of the environments; the wall was displaced randomly by a distance from -20 to 20 m in x direction.

The target was a red textured cylinder, 3 m tall, with a radius of 0.2 m. The car was 3.6 m long, 1.8 m wide, and 1.5 m tall (see Figure 2). The car appeared at the origin (x = 0, z = 0 m) at the beginning of each trial, facing the positive z direction, and moved straight ahead along a green guidance strip (14 m long) on the ground. At the end of the strip (x = 0, z = 14 m), the target appeared 40 m ahead and 12 m to the left of the car (x = –12, z = 54 m, i.e. 16.67° to the left relative to the z axis), and moved rightward on a path parallel to the x axis (see Figure 3). Participants steered the car to intercept the target. The initial location and moving direction of the target were mirrored left/right about the z axis in different trials and data were collapsed in the analysis. A trial ended if the center of the car was within a distance of 0.8 m to the target center or if the car went beyond the line z = 54 m. An environment similar to the textured-ground environment has been used previously in Zhao et al. (2019).

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Design and procedure.

The target moved at 4, 5 or 6 m/s on a trial. The environment and target speed yielded a 2 (environment) x 3 (target speed) within-participants factorial design. The two environments were blocked and their sequence was counterbalanced between participants. Each block consisted of 10 sub-blocks, each of which comprised 6 trials (3 target speeds by 2 repetitions) presented in random order. The first 12 trials (2 sub-blocks) in each block were eliminated from data analysis as practice trials. Before the interception task, we adjusted the HMD for each participant for comfortable wearing. In addition, all participants verbally confirmed clear views of the experimental environments. An experimental session lasted for about 45 min.

Data analysis.

Since participants could move their head freely during interception and the car was the end effector, we used the car's position and orientation for data analysis. Since the length of the car was 3.6 m, we defined a trial as a successful interception if the distance between the target and the car's center was smaller than 1.8 m. The interception location in a trial was defined by the car's closest location to the target. We took the x axis as the allocentric reference axis for the target's bearing and the car's heading. We computed the target's bearing angle ψ_i relative to this reference axis on each frame according to the following equation:

$$\psi_i = arccot\ [(X_i - x_i) / (Z_i - z_i)\ ] \qquad (2)$$

where (X_i, Z_i) and (x_i, z_i) are the coordinates of the target and the car respectively in the ith frame. The car's heading direction was recorded in each frame (φ_i on the ith frame), the target-heading in the ith frame was computed as $\beta_i = \psi_i - \varphi_i$. To compute the absolute rate of change in the target-heading, we divided its absolute difference between two successive frames by the duration

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between the two frames. We used the same way to compute the absolute rate of change in the target's bearing and the car's heading.

When the car came close to the target toward the end of interception, both the target's bearing and the target-heading angles usually changed quickly due to the short distance between the car and the target. To eliminate these data, we truncated each trial at the point in time when the center of the car reached a distance of 3.6 m to the target (e.g., see Lenoir, Musch, Janssens, Thiery, & Uyttenhove, 1999). Finally, the normalized mean time series of interception paths (the x and z position), as well as those of target-heading, bearing, and their absolute rate of change were computed. Because of the variable trial durations, this was done by normalizing each trial to a length of 50 data points. Specifically, the raw data points of each trial were divided into 50 bins with each bin containing an approximately equal number of data points; then the first data point in each bin was set as the value of the bin. Subsequently, the mean timeseries in each bin was computed across trials for each subject to yield a normalized mean time series for each condition. A similar data analysis was used in Zhao et al. (2019).

Results

Interception paths.

Twelve participants completed 1152 experimental trials in total. They intercepted the target successfully on 1150 trials, indicating that they understood the task and were able to perform the task successfully in most of the trials. The two failed trials were excluded from subsequent data analysis. Figure 4 shows each participant's mean interception paths, represented with the same color across target speeds and environments. Different participants produced interception paths with different degrees of curvature, which is consistent with the CTH strategy. Meanwhile, stable patterns of interception paths were observed within individual participants

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across environments and target speeds. Note that one participant produced the most linear interception paths in all conditions (the blue dashed curves in Figure 4). In this figure, participants' interception paths in different environments appear similar. To closely examine the influence of different conditions on interception paths, we analyzed the interception location and the mid-point location of interception paths. A two-way repeated-measures analysis of variance (ANOVA) with Greenhouse-Geisser corrections on interception location indicated only a significant main effect of target speed, $F(2, 22) = 219.501$, $p < 0.01$, $\eta_p^2 = .952$, but no significant main effect of environment, $F(1, 11) = .023$, $p = .883$, or significant interaction between them $F(2, 22) = 0.236$, $p = .700$. Since participants' interception paths always ranged from 14 m to 54 m in the z direction (see Figure 3), we defined the mid-point location of an interception path as the location with z = 34 m. The same analysis on the mid-point location gave the similar results: only a significant main effect of target speed, $F(2, 22) = 35.600$, $p < 0.01$, $\eta_p^2 = .764$, but no significant main effect of environment, $F(1, 11) = 2.673$, $p = .130$, or significant interaction between them $F(2, 22) = 0.265$, $p = .769$, was found. The results of the interception location and the mid-point location suggest that, although the plant-wall environment provided richer visual information about allocentric reference frames and richer optic flow, it did not significantly influence participants' steering. Their steering in the two environments can thus be explained by a single interception strategy. Therefore, we collapsed the data across the two environments in the following analysis.

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The target's bearing angle and the target-heading angle.

To examine which strategy better explains participants' steering, we computed the normalized time series of the target's bearing angle and the target-heading angle for each participant. Figure 5a shows the normalized time series of the target's bearing angle. Since the angle is defined with respect to an allocentric reference frame, we labeled the x-z axes in the figure accordingly. The figure shows that, during interception, the target's bearing angle continuously changed, albeit by different amounts between different participants. Note that the target's bearing angle changed little in one participant (represented as the blue dashed curves in Figure 5a). Figure 5b shows the target-heading angle. Since the angle is defined with reference to the heading direction, we fixed and labeled the heading direction as one axis in the figure. The target-heading angle, by contrast, changed by different amounts in different participants early during interception, then it remained approximately constant until interception in all participants.

--- Insert Figure 5 about here ---

--- Insert Table 1 about here ---

To compare the changes in the target's bearing and the target-heading angles, we averaged the absolute rate of change of these angles separately over the last 40% of the interception trajectory for each participant at each target speed (i.e., from 60% to 100% of an interception course). The means across participants are listed in Table 1. Note that, for the particular participant who produced the most linear interception paths, the absolute rate of change of the target's bearing angle was 1.54, 1.63, and 1.35 °/s for target speed of 4, 5, and 6 m/s, respectively. A paired t-test across target speeds indicated that the mean rate of change of

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the target's bearing angle was significantly larger than that of the target-heading angle, $t(35) = 6.06$, $p < 0.01$, $d = 1.01$. The results suggest that interceptive steering is better accounted for by the CTH strategy than the CB strategy.

As the CTH strategy explained participants' interceptive steering better, we inspected the target-heading angle more closely. Mean final target-heading angles ranged from 8.24° to 57.22° (mean = 29.19°, SD = 11.98°) across target speeds and participants, indicating clear individual differences in their steering. To examine the stability of steering within participants, we computed the *SD* of the final target-heading angle within each participant, then averaged them across participants for each target speed, resulting in 5.29°, 5.93°, 7.36° for target speed of 4 m/s, 5 m/s, and 6 m/s, respectively. This result was corroborated by testing whether the deviations between subjects were smaller than the deviations between conditions (repeated measurements ANOVA $F(11,22) = 10.25$, $p<0.001$). The low values of the *SD* suggest stable patterns of steering within participants.

Discussion

In this experiment, we examined whether interceptive steering with rich cues to an allocentric reference frame is better accounted for by the CTH strategy or CB strategy. We examined participants' interceptions in the textured-ground and the plant-wall environments, with the latter providing richer visual information about allocentric reference frames and richer optic flow. We found similar patterns of steering in the two environments, suggesting that participants might use the same strategy to guide their interceptions. Whereas the patterns of interception paths, the target-heading angle, and the target's bearing angle varied between participants, they appeared stable within participants. The most important result is that all participants maintained the target-heading angle at an approximately constant value during

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interception, with its absolute rate of change significantly smaller than that of the target's bearing angle. The results suggest that locomotor interception is better accounted for by the CTH strategy rather than the CB strategy, consistent with the findings in Zhao et al. (2019).

However, we found that one particular participant produced linear interception paths with little change in the target's bearing angle in the two environments. This pattern of steering is consistent with both the CTH strategy and the CB strategy. Since the two strategies potentially could be used in these environments based on the available information about an allocentric reference frame, we cannot determine which strategy this participant used. To answer this question, we examined interceptions of this participant and other new participants in the green-ground environment in the next experiment.

Experiment 2

The green-ground environment consisted of only a gray sky and a green ground plane, without any visual information about allocentric reference frames. Because the CB strategy relies on the availability of such a reference frame, it cannot explain interceptive steering in this environment. Thus, even if participants produce linear interception paths with a constant target's bearing angle in this environment, this pattern of steering should not be attributed to the CB strategy. Instead, since the CTH does not require access to an allocentric reference frame and does not specify the value of the bearing angle throughout interception, a linear pattern of steering should be attributed to the CTH strategy.

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Methods

Participants.

The particular participant who produced almost linear interception paths in Experiment 1 participated in this experiment with five more students at the Technical University of Darmstadt (one woman, five men; Mage = 26.0 years, SDage = 5.8 years). They all had a driver's license for at least two years, and had normal or corrected-to-normal vision. They read and signed a consent form before the experiment and received participation credit afterward from the Institute of Psychology.

Apparatus, display, procedure, and design.

This experiment was similar to Experiment 1 with several changes. First, participants intercepted the target in the plant-wall environment and the green-ground environment (see Figure 2b and c), with the latter consisting of only a gray sky and a green ground plane with the same size as those in the other two environments. Second, the same target was used in the two environments but changed to a cylinder of solid red with the same 3D dimensions (see Figure 2c). Third, in both the environments the same green guidance strip appeared on the ground at the beginning of every trial, but reduced to 10.5 m long. Thus, it went out of view about 0.5 s before the target appeared. This was intended to reduce the possibility of participants potentially using the memory of an allocentric reference axis early during interception. Fourth, in each experimental session, participants began with 6 interceptions (3 target speed by 2 target direction) in the plant-wall environment for them to understand the task. After that, they continued to practice trials and experimental trials in each environment. The target also moved at 4, 5, or 6 m/s in a trial. The data were analyzed the same way as in experiment 1.

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Results

Interception paths.

Participants successfully intercepted the target in all trials. We again tested for differences in the interception locations with a two-way repeated-measures ANOVA (with Greenhouse-Geisser corrections) and found a significant effect of the target's speed ($F(2, 10) = 61.642$, $p < 0.01$, $\eta_p^2 = 0.925$), but no significant effect of the environment ($F(1, 5) = 5.297$, $p = 0.07$) or interaction between speed and environment, ($F(2, 10) = 4.913$), $p = 0.077$).

There were, however, marked differences, i.e. subjects produced interception paths with different degrees of curvature (see Figure 6). Note that the particular participant who produced the most linear paths in experiment 1 produced linear paths even in the green-ground environment (see the blue dashed curves in Figure 6). Since we aimed to examine participants' interceptions in the green-ground environment, we focused our analysis on the interceptions in this environment.

--- Insert Figure 6 about here ---

The target's bearing and the target-heading angles.

Figure 7 shows each participant's normalized mean time series of the target's bearing and the target-heading angles, respectively, in the green-ground environment. The target's bearing angle continuously changed during interception, by different amounts in different participants. Note the small changes of the target's bearing angle in the particular participant who produced the most linear interception paths (the blue dashed curves in Figure 7). For this participant, the absolute rate of change of the target's bearing angle in the last 20 data points corresponding to

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the last 40% of interception trajectory was 3.42, 5.82, 1.88 °/s for target speed of 4, 5, and 6m/s, respectively (see Table 2).

--- Insert Figure 7 about here ---

Although the target-heading angle changed by different amounts in different participants early during interception, it subsequently remained approximately constant in all participants, which is consistent with the CTH strategy (see Figure 7). The absolute rate of change of the target-heading angle in the last 20 data points is listed in Table 2. Mean final target-heading angle ranged from -3.51° to 43.74° across target speeds and participants, indicating obvious individual differences in participants' steering. The mean of the within-participant SD of final target-heading angle was 5.75°, 4.65°, and 5.47° for target speed of 4, 5, and 6 m/s, respectively, which indicates a stable pattern of steering within participants.

--- Insert Table 2 about here ---

Discussion

In this experiment, we examined whether interceptive steering without access to an allocentric reference frame could result in steering that is both consistent with the CTH and CB strategies. Specifically, we tested whether the steering of one particular participant, whose steering was consistent with both strategies in the first experiment, continued to show straight trajectories with a constant bearing angle. Interception paths of this participant still appeared linear with little change in the target's bearing angle in this environment, a similar pattern of steering to that in Experiment 1. Since the green-ground environment provided no visual

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information about allocentric reference frames, the participant could not use the CB strategy. Therefore, the participant's interception should be attributed to the CTH strategy rather than the CB strategy. Moreover, the target-heading angle was maintained at an approximately constant value in all participants, consistent with the CTH strategy. Participants' use of the CTH strategy in different environments, especially in the green-ground environment with scarce visual information, implies that the CTH strategy is reliable and robust in guiding locomotor interception across different environments.

Some studies have shown that different environments may influence the actor's perception of the target's speed and hence the actor's interceptive steering. Lenoir, Savelsbergh et al. (1999) suggest that, during locomotor interception, a stationary background with texture increases the perceived speed of a moving target, compared with a background without texture. Moreover, Fajen and Warren (2004) found that the target-heading angle was larger in interceptions in a room with textured walls and ceilings than in an empty black space. In the current experiment, though the influence of the environment on interception location was not significant, we may see some trace of the influence of the environment in a couple of participants. They steered in a direction less ahead of the target in the green-ground environment than in the plant-wall environment, resulting in a relatively more curved path and a further interception location in the green-ground environment (e.g. see the red curves for interceptions of the fastest target in Figure 6).

General Discussion

In the current study, to critically examine which strategy participants would use for locomotor interception, we manipulated the visual information about allocentric reference frames

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in three virtual environments and tested participants' interceptive steering in them. While individual differences in participants' steering trajectories were evident, we found statistical evidence for a stable pattern of steering within participants, i.e., participants maintained the target-heading angle at an approximately constant value. In contrast, the target's bearing angle continuously changed in most of the participants. Thus, subjects did not adopt the CB strategy, although the plant-wall environment provided richer cues to an allocentric reference frame. Only one particular participant produced linear interception paths with little change in the target's bearing angle during interception, which seemed consistent with the CTH strategy as well as the CB strategy. However, this pattern of steering was also observed in the green-ground environment where the CB strategy could not be used due to the absence of visual information about allocentric reference frames. Therefore, this pattern of steering should be attributed to the CTH strategy rather than the CB strategy. This result furthermore underlines that observing a linear trajectory does not imply that participants necessarily follow the CB strategy. The overall results add important evidence for the conclusion drawn from Zhao et al. (2019), i.e., interceptive steering is better accounted for by the CTH strategy.

Although the CTH strategy provides a better explanation for interceptive steering, it cannot provide a complete explanation for all aspects of participants' steering. Since the CTH strategy prescribes only the rate of change of the target-heading angle but not its value, the strategy itself cannot explain the individual differences in participants' steering in this study. To address this question, further research needs to develop a computational account for interceptive steering. One such approach could be based on stochastic optimal control, which has recently been shown to account for the locomotor interception of a fly ball (Belousov, Neumann, Rothkopf, and Peters, 2016).

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Alternative accounts could be based on a hybrid strategy. For example, some hybrid strategies have been proposed for both manual interception and locomotor interception. In de la Malla and López-Moliner (2015), participants used their hand to catch a ball approaching on a parabolic trajectory. Participants' hand movements were more strongly influenced by the ball's elevation angle and its derivative during the earlier phase of catching whereas they were more strongly influenced by the ball's looming information in the later phase. Therefore, the authors proposed a hybrid strategy in which manual interception is guided by different information at different stages. For locomotor interception by speed adjustment, Diaz, Phillips, and Fajen (2009) proposed a hybrid control model which combines the prediction of target motion with the CTH strategy. For example, in one of their experiments, participants' speed adjustment was inconsistent with the CTH strategy during the early phase of interception. To account for participants' speed adjustment, a hybrid model was proposed, in which the actor predicts the target's motion in a short future time (about 0.5-1.0 s) and adjusts its moving speed to null the change in the target-heading angle at the future time.

Conclusion

In the three virtual environments with different amounts of visual information about allocentric reference frames, we observed clear individual differences in participants' steering, but stable patterns of steering within participants. With the target's bearing angle continuously changing in most participants, all participants maintained the target-heading angle at an approximately constant value. Though one particular participant produced linear interception paths with little change in the target's bearing angle, this pattern of steering was even observed

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in the environment where the CB strategy cannot be used. The overall results suggest that locomotor interception by car steering is better accounted for by the CTH strategy.

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Figure Captions

Figure 1. The CTH and the CB strategies and their associated angular quantities. (a) Definition of variables describing the interception of a moving target: velocity of the target (vt), velocity of the actor (va), heading angle of the actor (φ) relative to an allocentric reference direction, bearing angle of the moving target (ψ) relative to the same allocentric reference direction, and the difference between these two angles, which is the target heading angle (β = ψ – φ). (b) The CTH strategy with its associated constraint. (c) The CB strategy with its associated constraints.

Figure 2. Representative views of a participant in the three environments. (a) The textured ground environment at the moment when the target appears. (b) The plant wall environment at a moment during interception. (c) The green ground environment at a moment during interception.

Figure 3. Layout of the initial locations of the car and the target in the x-z plane. The wall's exact location is z = 100 m, but is positioned closer to the car in this figure.

Figure 4. Each participant's mean interception paths at the different target speeds (vt), in different environments. Each participant's paths are presented in the same color across the six conditions. The same color and style of curves are used for the respective participants in the following figures in Experiment 1.

Figure 5. Each participant's normalized mean time series of the target's bearing angle (a) and the target heading angle (b). The outer circles in the polar coordinates represent the start of

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interceptions, i.e. the first data point of the normalized time series; the inner circles 60% of interception courses, i.e. the 30th data point of the normalized time series.

Figure 6. Each participant's mean interception paths at different target speeds (vt), in different environments. Each participant's paths are presented in the same color across the conditions. The same color and style of curves are used for the respective participants in the following figures in Experiment 2.

Figure 7. Each participant's normalized mean time series of the target's bearing angle and the target heading angle. The outer circles in the polar coordinates represent the start of interceptions, the inner circles 60% of interception courses.

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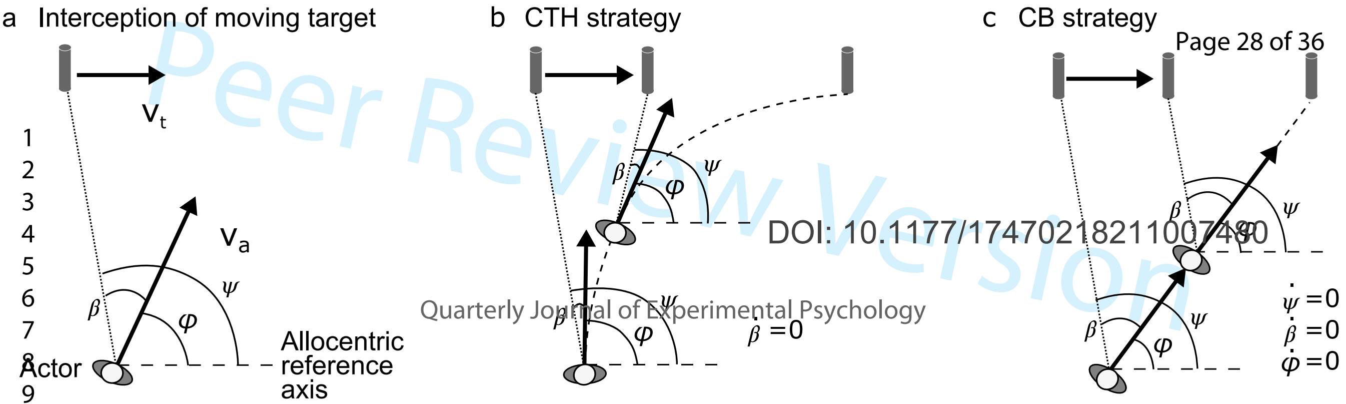

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a. Textured-ground b. Plant-wall c. Green-ground

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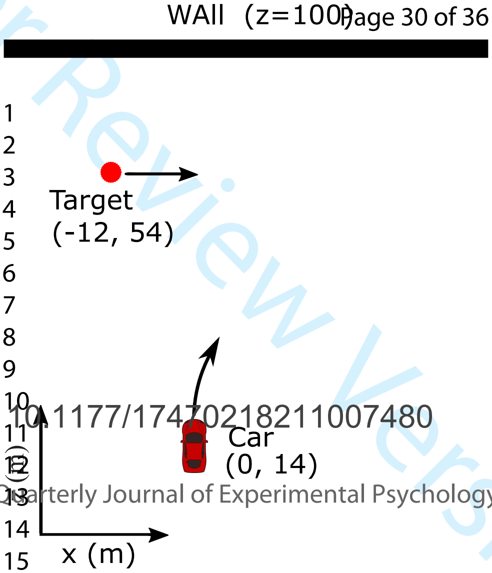

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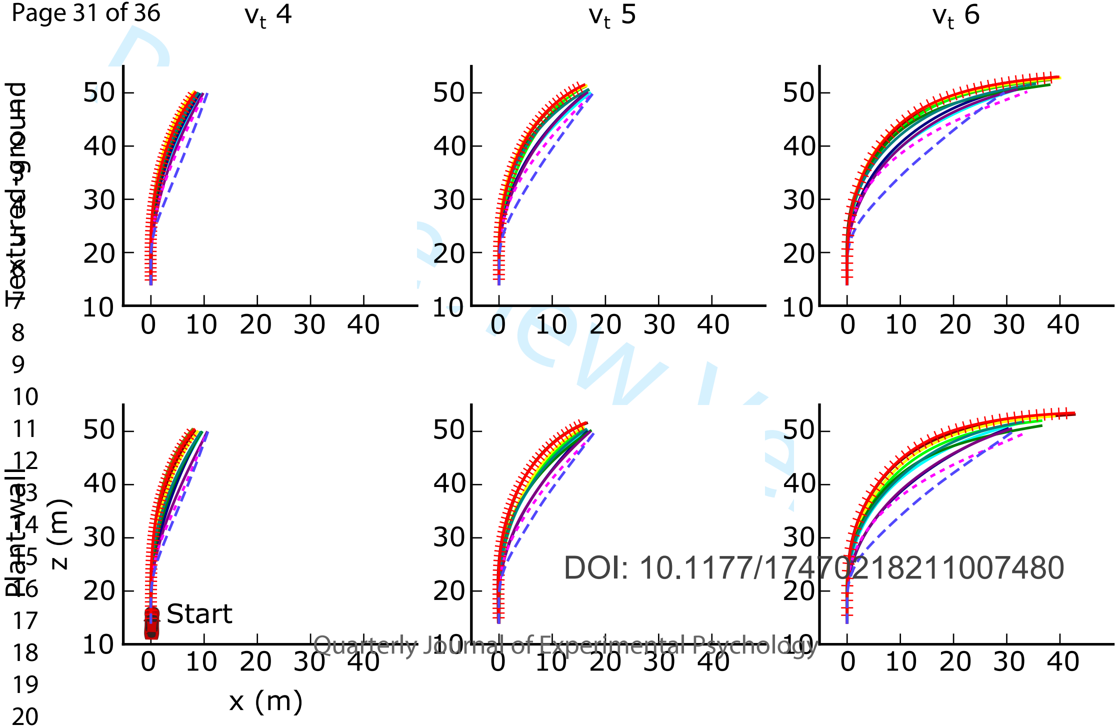

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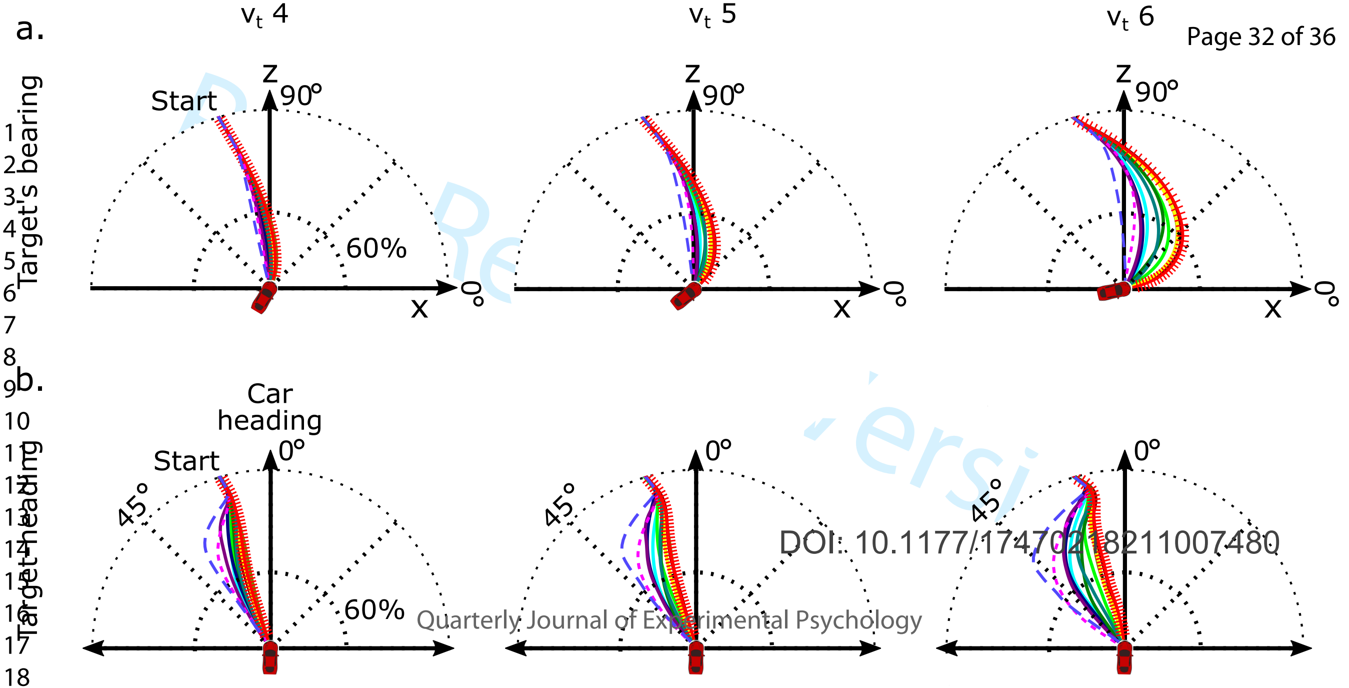

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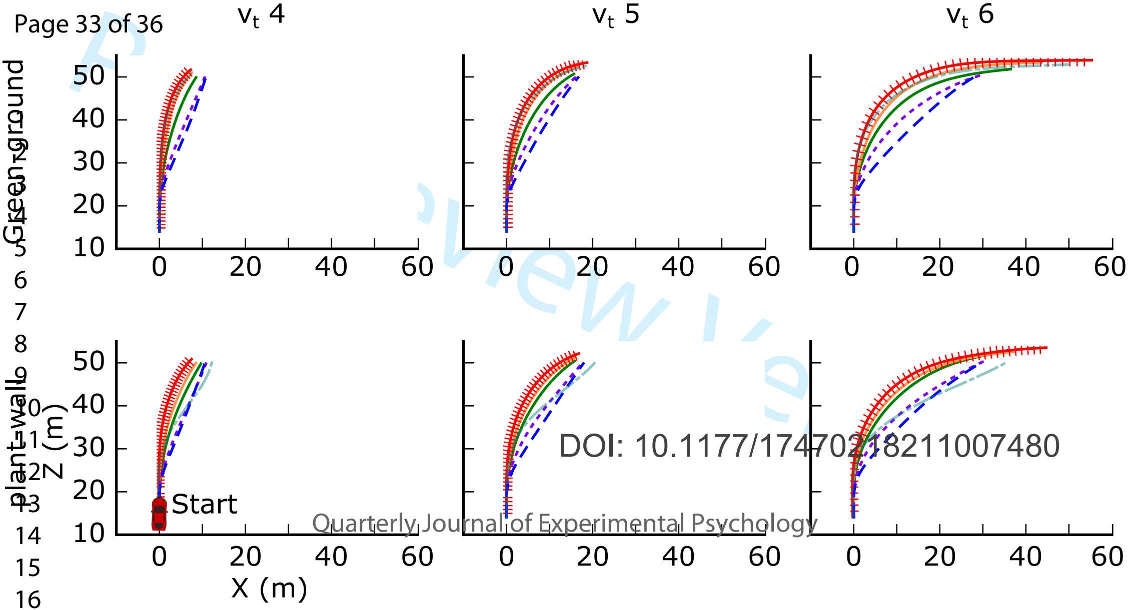

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Green-ground environment

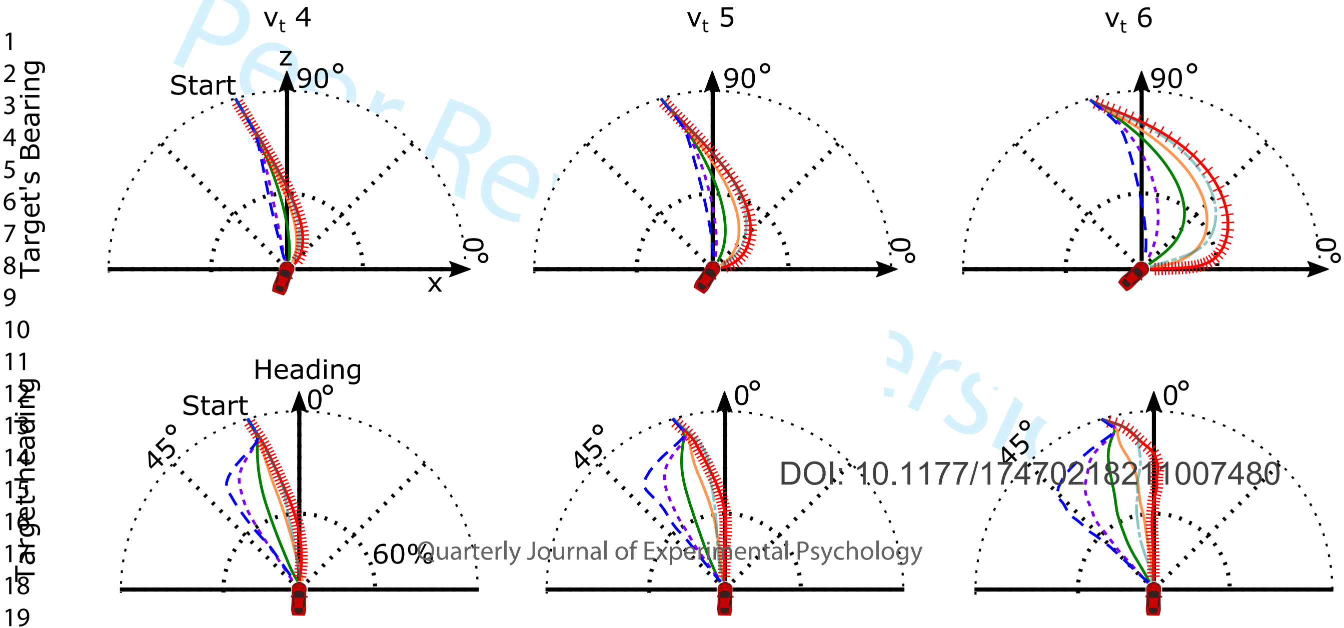

Table 1.

Mean absolute rate of change over the last 40% of trajectories corresponding to the last 20 data points.

Target Speed	Target-heading		Target's bearing	
	M (*SD*)	Range	*M* (*SD*)	Range
v_t 4	2.57 (0.51)	[1.66, 3.36]	5.88 (3.46)	[1.54, 11.83]
v_t 5	2.95 (0.93)	[1.82, 5.14]	8.99 (5.22)	[1.63, 15.68]
v_t 6	2.36 (0.38)	[1.63, 2.99]	6.17 (2.53)	[1.35, 8.44]

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Table 2.

Mean absolute rate of change over the last 40% of trajectories corresponding to the last 20 data points.

Target speed	Target-heading		Target's bearing	
	M (*SD*)	Range	*M* (*SD*)	Range
v_t 4	2.81 (1.16)	[1.30, 4.49]	12.79 (8.67)	[3.42, 23.77]
v_t 5	2.39 (0.58)	[1.77, 3.36]	13.71 (6.18)	[5.82, 20.31]
v_t 6	2.13 (0.86)	[1.01, 3.35]	5.07 (2.12)	[1.88, 6.90]

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