Psychon Bull Rev
DOI 10.3758/s13423-013-0412-5

BRIEF REPORT

Blind(fold)ed by science: A constant target-heading angle is used in visual and nonvisual pursuit

Dennis M. Shaffer · Igor Dolgov · Eric Mcmanama · Charles Swank · Andrew B. Maynor · Kahlin Kelly · John G. Neuhoff

Abstract Previous work investigating the strategies that observers use to intercept moving targets has shown that observers maintain a constant target-heading angle (CTHA) to achieve interception. Most of this work has concluded or indirectly assumed that vision is necessary to do this. We investigated whether blindfolded pursuers chasing a ball carrier holding a beeping football would utilize the same strategy that sighted observers use to chase a ball carrier. Results confirm that both blindfolded and sighted pursuers use a CTHA strategy in order to intercept targets, whether jogging or walking and irrespective of football experience and path and speed deviations of the ball carrier during the course of the pursuit. This work shows that the mechanisms involved in intercepting moving targets may be designed to use different sensory mechanisms in order to drive behavior that leads to the same end result. This has potential implications for the supramodal representation of motion perception in the human brain.

Keywords Navigation · Visual perception

We have all heard the saying "I could do that blindfolded," referring to the ease with which we might be able to perform a task. We were interested in investigating whether blindfolded observers would use hearing to implement the same strategy that sighted observers use to intercept ball carriers using vision. The primary strategy used by humans to intercept moving targets is to maintain a *constant target-heading angle* (or CTHA) (Fajen & Warren, 2007; Shaffer & Gregory, 2009).[1] A diagram of the CTHA strategy is shown in the left panel of Fig. 1. The goals of this strategy are to aim slightly ahead of where the target is going (i.e., keep $\beta > 0$) and to maintain a constant angle (i.e., keep $\beta_1 = \beta_2 = \beta_n$) so that the derivative of the angle with respect to time is equal to zero (i.e., $d\beta/dt = 0$). This strategy produces a collision course as long as β is less than 90°and the pursuer's trajectory approximates a straight line (Fajen & Warren, 2004). An abundance of evidence from humans interacting with targets has confirmed use of the CTHA strategy. People intercepting targets while riding on a tricycle (Lenoir, Musch, Janssens, Thiery, & Uyttenhove, 1999), walking on a treadmill (Chardenon, Montagne, Buekers, & Lauent, 2002), walking in a virtual environment (Fajen & Warren, 2004), and chasing other people (Shaffer & Gregory, 2009) have all been shown to use a CTHA strategy.

Two other possible strategies include *pursuit* and *pure prediction*. A diagram of the pursuit strategy is shown in the right panel of Fig. 1. The pursuit strategy has also been called *aiming*, *homing*, and *centering*. The pursuer's objective is to aim directly at the ball carrier as he pursues him. In this strategy, the pursuer aims directly toward the ball carrier at each instant in time, so that $\beta = 0$ at all times. Houseflies chasing one another, teleost fish chasing food from above, and humans walking to stationary or slowly moving targets

D. M. Shaffer (✉) · E. Mcmanama · C. Swank · A. B. Maynor · K. Kelly
Department of Psychology, The Ohio State University–Mansfield, 1760 University Drive,
Mansfield, OH 44906, USA
e-mail: Shaffer.247@osu.edu

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

J. G. Neuhoff
College of Wooster, Wooster, OH, USA

[1] Fajen and Warren (2007) used simulated data to show that this kind of model describes human pursuit best, when factoring out the turning rate. They call this using a constant bearing angle (CBA). The two (CTHA and CBA) are functionally equivalent, so long as the pursuer is aiming ahead of the ball carrier and running in a straight path toward the target (Fajen & Warren, 2007). Additionally, in that study, participants were walking, and not running, toward targets.

Published online: 26 February 2013

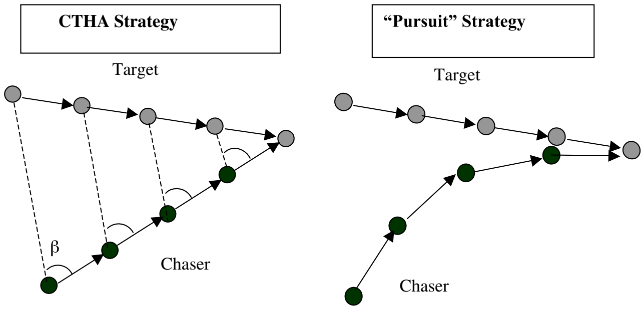


Fig. 1 The constant target-heading angle (CTHA) strategy and the pursuit strategy

all use this strategy (Fajen & Warren, 2003; Lanchester & Mark, 1975; Land & Collett, 1974; Rushton, Harris, Lloyd, & Wann, 1998). A less likely alternative is a more classic predictive strategy, which we term *pure prediction*. In this strategy, the pursuer arrives at the eventual perceived interception point and waits until the ball carrier arrives. Archer fish catching prey use this strategy (Rossel, Corlija, & Schuster, 2002; Wohl & Schuster, 2006).

Research investigating interception of objects on the ground plane while walking and running has demonstrated that retinal (or optic) flow, gaze angle, visually perceived target location, or some combination thereof contribute to navigation (Bastin, Calvin, & Montagne, 2006; Crowell, Banks, Shenoy, & Andersen, 1998; Fajen & Warren, 2004, 2007; Rushton et al., 1998; Warren, 1998; Wilkie & Wann, 2005). One of the underlying assumptions of the vast majority of this work is that vision is necessary for interception.

In the present work, we examined whether vision is necessary to use the CTHA strategy. Specifically, we investigated whether blindfolded observers utilize hearing to induce the same CTHA strategy that sighted observers use when pursuing a ball carrier, a scenario commonly found in American football. Defensive players in American football must be able to know precisely the angle and speed at which to run in order to competently and quickly intercept and tackle an opponent who has the ball. We implemented a methodology that reflects this type of pursuit.

Experiment 1

Method

Sighted condition

Participants Three males (mean age, 28.67 years) who were experienced with pursuing ball carriers in American football participated in both the sighted and blindfolded conditions.

Materials We outlined a 20 × 20 m area in an indoor gymnasium. We then marked angles from one corner of the outlined area where the ball carrier would begin jogging. These angles were 20°, 40°, 60°, and 80°. Another ground marker identified the midway point in the grid for each angle, so the ball carrier knew when to change speed and/or change angle direction. The chaser started 20 m directly to the right of the starting position of the ball carrier and was instructed to touch the runner before he ran out of the grid. Due to the large amount of running, each of the 3 participants were rotated as ball carrier or chaser. A diagram of the layout is shown in Fig. 2.

Design and procedure For a total of 96 trials, one chaser tried to touch the ball carrier. The 96 trials were split equally into the four initial angle straight-line paths that runners were instructed to run along, specified as 20°, 40°, 60°, and 80° from the ball carriers' starting position. We also varied whether the ball carrier moved at a constant speed or sped up midway, because we wanted to evaluate how the strategy (or strategies) might be affected not only by a change in direction, but also by a change in speed. Thus, for each initial angle, the ball carrier ran in one of the following ways: (1) constant-speed/straight-line, (2) constant-speed/cut-up, (3) constant-speed/cut-down, (4) speed-up/straight-line, (5) speed-up/cut-up, and (6) speed-up/cut-down. In the *cut* condition, the ball carrier ran along a straight line along one of the angle paths from his initial starting position, and midway changed the angle he was jogging by 20°. For instance, if the ball carrier was instructed to begin running along the 20° path and cut up, he would run until the midway point and then begin running at the cone specifying 40°. In the *cut-down* condition, the runner in the previous example would change midway to running in a straight line to 0°. In the speed-up condition, ball carriers were told to run faster after the midway point than they were running before the midway point.

To summarize, 96 total trials were performed and were split into four different groups of trials on the basis of the initial angle, for a total of 24 trials for each initial angle. For one third of these trials (i.e., 8), the runner ran in a straight line. For another 8, he cut up, and for the final 8, he cut down. For half of each of the straight-line/cut-up/cut-down trials (i.e., 4), the runner ran at a constant speed, and for 4 trials, the runner sped up. All 96 trials were then randomized. The chaser was kept unaware of the condition before the trial started.

To reduce practice effects, all 3 participants were run through the blindfolded condition first and then the sighted condition.

A Vicon eight-camera ViconMX™ motion capture system with 1-cm accuracy recorded chaser head position and ball position at 60 Hz.

Blindfolded condition

The participants, design, and procedure were virtually identical to those in the sighted condition, with three

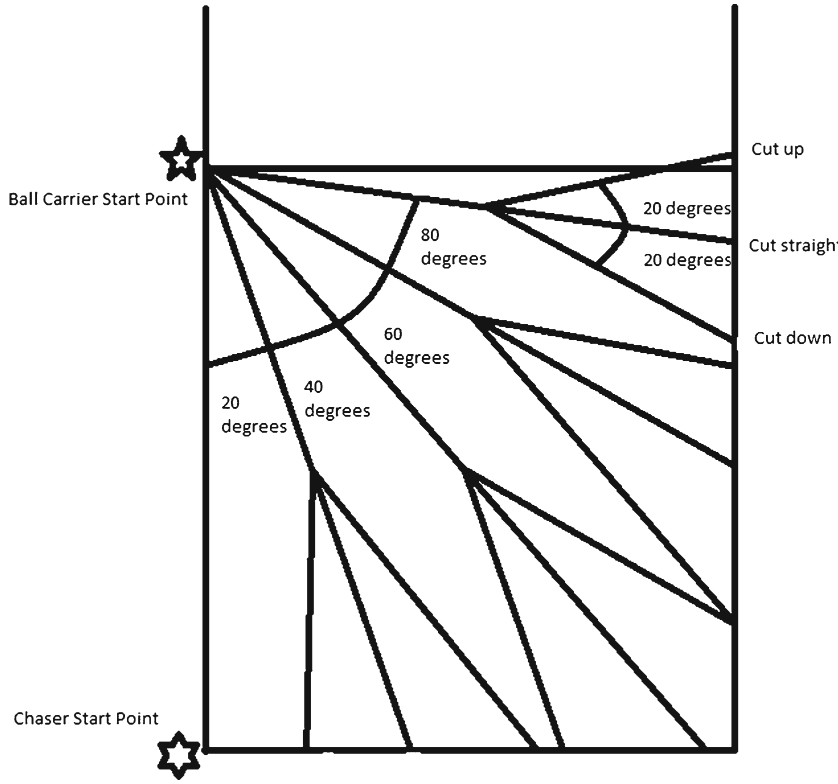


Fig. 2 Methodology for Experiment 1. Ball carrier ran along the paths shown. Refer to the Method section of Experiment 1 for further details

notable exceptions. First, the chaser was blindfolded with a sleeping mask. We tested whether participants could see through the mask, and none of the participants reported any ability to do so. Second, the ball carrier held a beeping foam football. The football emitted an intermittent 2800-Hz sine wave tone that was 74 dBA measured at 1 m. The tone was 330 ms in duration with an interonset interval (IOI) of 600 ms and beeped continuously for the duration of each trial. Ball carriers announced that they had begun walking so that the chasers would know when to start. Chasers were instructed to follow the sound of the beep in order to intercept the ball carrier. Third, we eliminated the speed-up condition, which reduced the number of trials to 72. This was done because the participants had never pursued a beeping ball while blindfolded before and we wanted the chasers to have a fair chance at intercepting the ball carrier. Eighteen trials were run per angle, with 6 of each of these 18 trials as either cut up, cut down, or straight. All of the 72 trials were randomized.

To summarize, we expected both sighted and blindfolded pursuers to use a CTHA by jogging in a relatively straight line (Fajen & Warren, 2004), jogging in such a way as to aim ahead of the instantaneous position of the target (or maintaining a target-heading angle greater than 0) and, in so doing, maintain a change in the target-heading angle that hovered around 0.

Results

Overall

Ninety-three of 96 trials (~97%) in which the chaser successfully touched the ball carrier in the sighted condition were coded. Three trials were uncodable because the beeping football was recorded by the Vicon system only intermittently throughout these trials. In the blindfolded condition, 17 trials were uncodable because the beeping football was recorded by the Vicon system only intermittently throughout these trials. In both cases, this was most likely due to the football being occluded by the hand and/or arm of the ball carrier at times. Forty of the remaining 55 trials (~73%) in which the chaser successfully touched the ball carrier in the blindfolded condition were coded and analyzed.

Blindfolded versus sighted conditions

Jogging paths of pursuers On the cut trials, the pursuer's path after the ball carrier made a cut was analyzed as a separate path for regression analysis. Therefore, cut trials have both linear and polynomial regression analyses applied twice per trial. This affects the degrees of freedom because straight trials have only one linear and polynomial regression analysis per trial. There were 31 sighted straight trials and 16 blindfolded straight trials (straight trials are defined as trials that were intentionally straight or trials on which the ball carrier was intercepted prior to making a 20° cut). There were 62 sighted cut trials and 24 blindfolded cut trials. Linear regression analyses indicated that straight lines accounted for over 94% of the variance in jogging paths of pursuers in the sighted condition (SD = .17) versus 93% of the variance in the blindfolded condition (SD =.17). A one-way analysis of variance (ANOVA) revealed no difference between these conditions, $F(1, 217) = 0.01$, $p > .1$. A 2 × 2 factorial ANOVA with before/after and cut-up/cut-down as conditions found a significant interaction showing that significantly less variance was accounted for in the cutting-down condition (M = .8, SD = .29) than in the cutting-up condition (M = .95, SD = .16) after the cut was made, $F(1, 168) = 8.77$, $p < .001$ (both precut and straight trials, R^2s ~.98). This was a small effect, $\eta^2 = .05$. We also analyzed how much variance a polynomial (one curve) fit accounted for in the walking paths of the pursuers. In the sighted condition, the polynomial accounted for 96% of the variance in the jogging paths of the pursuers (SD = .12) versus 95% of the variance in the blindfolded condition (SD = .13). A one-way ANOVA again revealed no difference between the sighted and blindfolded conditions, $F(1, 217) = 0.10$, $p > .1$. A one-sample t-test comparing linear and polynomial fits and using the change in R^2 showed that polynomial fits accounted for significantly more variance than did linear fits, $t(218) = 4.84$, $p < .001$. This was a medium-sized effect, Cohen's $d = 0.33$. Representative jogging paths in the sighted condition are shown in the left panels of Fig. 3, while representative jogging paths in the blindfolded condition are shown in the left panels of Fig. 4.

Target-heading angle We measured target-heading angle at each 1/60th of a second. For the cut trials, we again divided the trial where the cut was made and calculated the target-heading angle prior to and after the cut. For all conditions, the target-heading angle was well above 0, consistent with using a CTHA. For the trials on which there was no cut, the mean target-heading angle, β, for the sighted condition was 55.75° (SD = 34.92°), while the mean target-heading angle, β, for the blindfolded condition was 50.69° (SD = 35.76°). For the trials on which the ball carrier cut, the mean target-heading angle in the sighted condition was 56.33° (SD = 38.5°) and 41.57° (SD = 23.17°) prior to the cut and after the cut, respectively. The mean target-heading angle, β, in the blindfolded condition was 60.01° (SD = 38.89°) and 52.82° (SD = 39.53°) prior to the cut and after the cut, respectively.

Change in the target-heading angle In order to calculate the mean change in the target-heading angle, $d\beta/dt$, we first computed $d\beta/dt$ at each instant throughout each trial. The mean change in the target-heading angle for the sighted condition was 0.08° (SD = 0.24°). In order to test whether $d\beta/dt$ was significantly different than 0, we performed a one-sample t-test that showed that $d\beta/dt$ was not statistically different from 0, $t(28301) = 0.32$, $p > .5$. We found that the mean change in the target-heading angle, $d\beta/dt$, for the sighted condition was statistically no different from that for the blindfolded condition, $F(1, 54289) = 0.07$, $p > .5$ (blindfolded condition, M = .02, SD = .25). Plots of changes in target-heading angle over time corresponding to the sighted jogging path trials shown in the left panels of Fig. 3 are shown in the right panels of Fig. 3. Plots of changes in target-heading angle over time corresponding to the blindfolded jogging path trials shown in the left panels of Fig. 4 are shown in the right panels of Fig. 4.

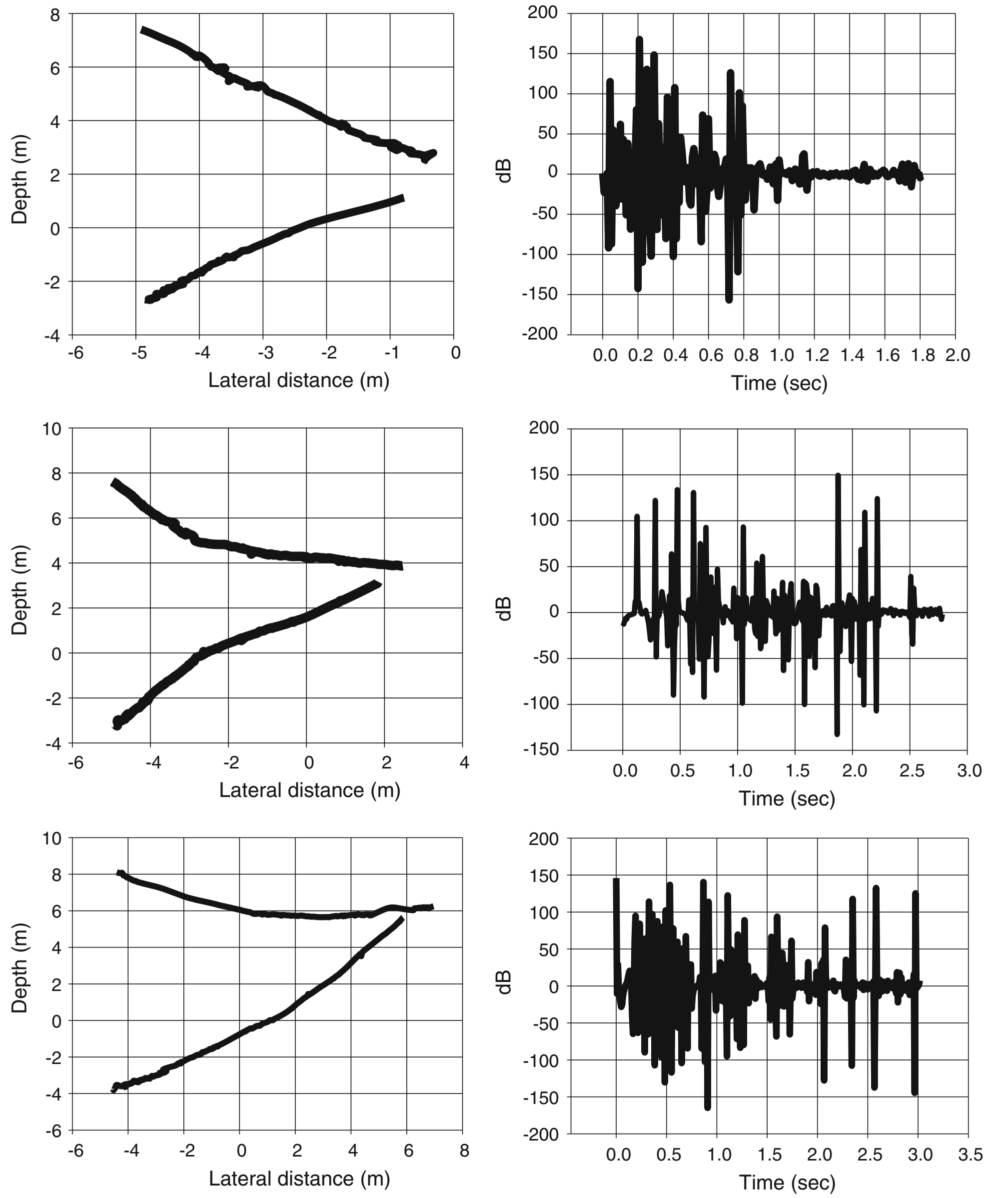
Change in target-heading angle precut versus postcut versus no cut In order to test whether maintaining a CTHA still works when the ball carrier's trajectory deviates from a straight line and after a change in trajectory, as compared with before, we performed a 2 (vision condition: sighted/blindfolded) × 3 (cut portion: before-cut/after-cut/no-cut) factorial ANOVA. There was no main effect of cut portion, $F(2, 54285) = 0.02$, $p > .5$. Additionally, there was no difference in strategy taken before and after the cut between vision groups, since the interaction was not statistically significant, $F(2, 54285) = 0.01$, $p > .5$.

Misses Two raters put the misses into the following categories: (1) a curvilinear path similar to that shown in Fig. 1 (pursuit strategy) (for all of these, linear regression lines had very poor fits); (2) a straight path by eye and by regression fit—essentially a CTHA, but where the pursuer was too slow (trailed behind the ball carrier); (3) a straight path by eye and by regression fit where the pursuer arrived at the eventual destination point early. In these cases, pursuers arrived at the initial destination point early but were not able to touch the ball carrier (pure prediction). This sometimes resulted from pursuers waiting at the initial path (or precut) destination on cut trials and then not being able to move in time to catch the ball carrier after the cut; (4) either a straight path followed by a pursuit path or a pursuit path followed by a straight path (*combination* strategy). There was 100% agreement between raters.

There were no misses in the sighted condition. Of the 19 misses in the blindfolded condition, 12 consisted of trials on which the pursuer used pure prediction; they went to what they *thought* would be the eventual interception point and waited. On 3 trials they used CTHA but were too slow, and on 3 they used a combination strategy. On 1 trial, the pursuer used a pursuit strategy.

Pursuer speeds Average pursuer speeds were 1.98 m/s (SD = 1.19) and 1.02 m/s (SD = 0.8) for the sighted and

Fig. 3 Left panels: Representative running paths in the sighted condition. Right panels: Changes in the target-heading angle, *dβ/dt,* corresponding to the running paths shown in the left panels



blindfolded conditions, respectively. Ball carriers were jogging nearly twice as fast in the sighted condition as in the blindfolded condition.

Discussion

Experienced football players chasing a ball carrier used a CTHA strategy in order to intercept the ball carrier. Using this strategy did not change irrespective of whether the pursuers were sighted or blindfolded. While polynomial fits accounted for 2% more variance in both conditions, a CTHA still followed for two reasons. First, straight lines accounted for 93% and 94%, respectively, of the variance, overall, and 98% for straight trials and precut portions. Thus, it seems that the changes made by the pursuer in the direction of pursuit in the cut conditions resulted in dropping the variance accounted for from 98% to ~94%. The requirement of CTHA for the pursuit paths is to approximate straight lines, and accounting for ~94% of the variance overall was enough to do this, as evinced by the second reason. Second, the end result of the CTHA is that the change in the target-heading angle remains constant at 0, which it did. Thus, the CTHA strategy is robust because it works with slight deviations from the ideal situation.

Experiment 2

Experiment 1 showed that experienced football players jogging after a ball carrier use the CTHA strategy irrespective of whether they are sighted or blindfolded. We performed Experiment 2 for two main reasons. First, because the travel speed in the blindfolded condition was much slower than that

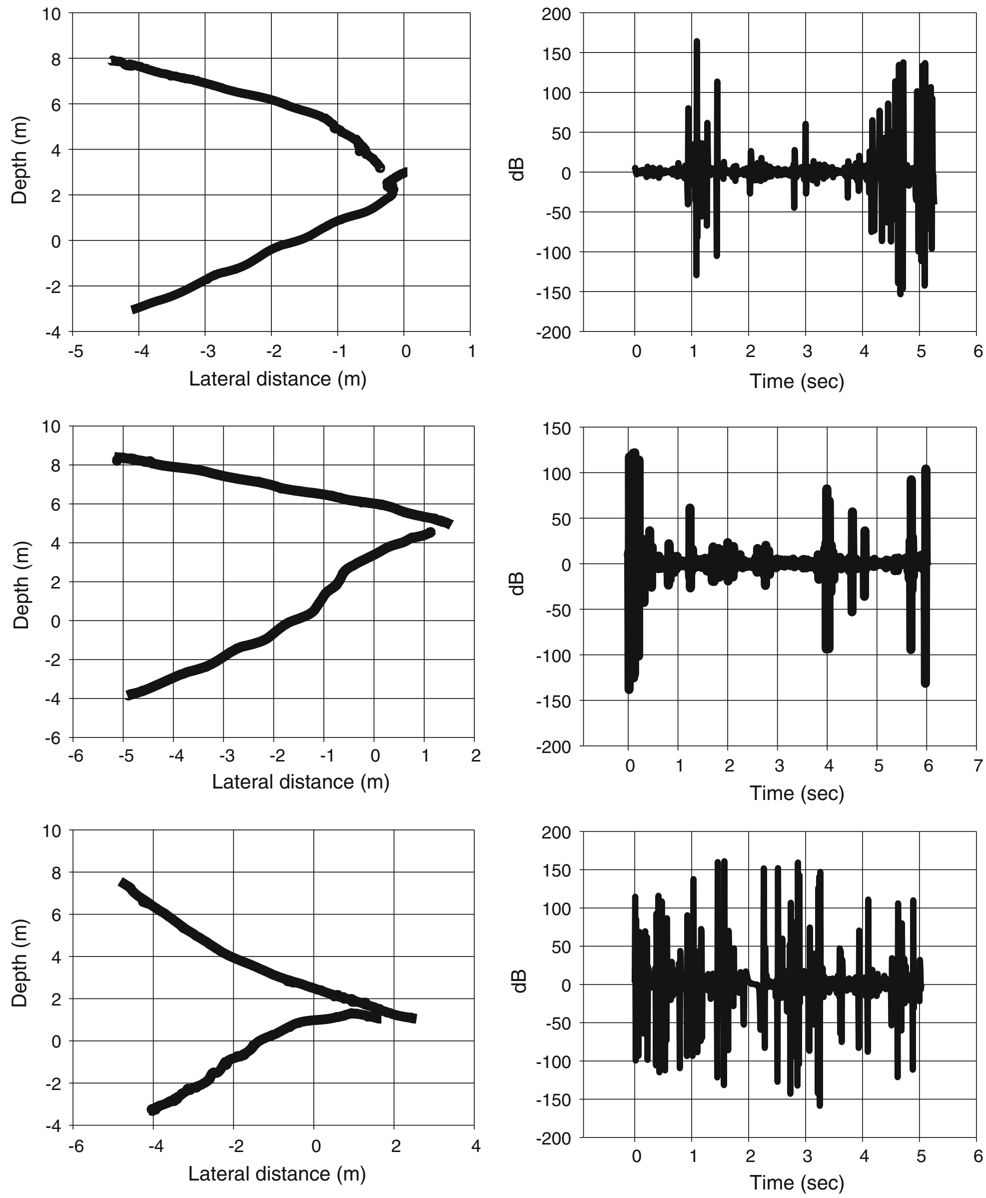


Fig. 4 Left panels: Representative running paths in the blindfolded condition. Right panels: Changes in the target-heading angle, *dβ/dt*, corresponding to the running paths shown in the left panels

in the sighted condition, it is difficult to compare the conditions in a straightforward manner. Second, using experienced players restricts the conclusions to the population of people with experience playing football. In order to generalize the findings to the general population, it is necessary to get a range of experience levels. Thus, in the following experiment, we had people who ranged from no experience with football to those who often play football perform the essence of the first experiment while walking sighted or blindfolded.

Method

Participants

Four males and 2 females (mean age, 25 years) with varying levels of experience playing American football participated in the experiment. We randomly assigned the 6 participants equally between blindfolded and sighted conditions.

Materials

We outlined a 20 × 20 m area in an indoor gymnasium. We then marked angles from one corner of the outlined area where the ball carrier would begin walking. These angles were 30°, 60°, and 90°. These were different than they were in Experiment 1 because we felt that the walking path angles themselves and the 20° cuts were not different enough from one another to be challenging enough for pursuers while they were walking. Another ground marker identified the midway point in the grid for each walking angle, so the ball carrier knew when to change direction. The chaser started 20 m directly to the right of the starting position of the ball carrier and was instructed to touch the ball carrier before he walked out of the grid.

Design and procedure

Participants were first asked to rate their football playing experience. A Likert scale assessed how much football-playing experience participants had. The scale was as follows: 1 = *I have never played*, 2 = *I have rarely played*, 3 = *I sometimes play*, 4 = *I play/played often* (this could be the equivalent of playing in high school), and 5 = *I play/played for an organized college level team*.

Sighted condition For a total of 81 trials (27 per chaser), one chaser tried to intercept the ball carrier. Each set of 27 trials was randomized so that the ball carrier traveled each initial pursuit path (30°, 60°, and 90°) 9 times. These nine trials were equally divided among walking a straight path the entire time, cutting up 30° midway, and cutting down 30° midway. Throughout the trials, the ball carrier used a normal walking pace each time so as to eliminate change in speed as a factor. The goal of the chasers on each trial attempt was to intercept the ball carrier before he reached the boundary of the 20 × 20 m outlined area, with the only restriction being that they could not run or jog to catch the ball carrier.

A Vicon eight-camera ViconMX™ motion capture system with 1-cm accuracy recorded chaser head position and ball position at 60 Hz.

Blindfolded condition The design and procedure for the blindfolded condition were identical to those in the sighted condition, with two exceptions. First, the chaser was blindfolded with a black bandana that was folded over several times. We tested whether participants could see through the mask by having them complete a forced choice task. The first participant was asked to identify which of two people had their hand up. They did this 10 times, and the person who had their hand up was decided by a coin toss. This participant identified which person had a hand up 4 times. We did this again with our second participant. This participant guessed correctly 8 out of 10 times. In order to test whether this person was "lucky" or could actually see out of the blindfold, we made the task a forced choice task with three options. Using this modified three-alternative forced choice task, the second participant was unable to guess correctly at all. We used the same three-alternative forced choice task for the third participant, who correctly guessed twice. Second, we attempted to use the beeping football again for this experiment. However, the first participant claimed not being able to hear the ball soon enough to follow it before it was too late to intercept the ball carrier. We believe that this was due to the fact that when one is walking, it is difficult to close the distance enough to potentially use auditory cues to one's advantage, whereas when jogging/running (as in Experiment 1), it is relatively easy to do this. Because of this, the ball carrier called out the word "ball." The male voice repeating the word "ball" had an average fundamental frequency of 120 Hz. The duration of the word was approximately 500 ms, with an 800-ms IOI. Participants reported that they had no problem hearing this from the beginning of the trial. Chasers were instructed to follow the sound of the ball carrier's voice in order to intercept him.

Each of the 6 people participated in either the blindfolded or the sighted condition, but not both. Additionally, participants were not allowed in the gym. This prevented all the participants from seeing the setup of the experiment and prevented them from watching ball carrier and pursuer movements.

Results

Overall

Seventy-eight of 81 trials (~96%) in which the chaser successfully touched the ball carrier in the sighted condition were coded and analyzed. On 3 trials, the pursuer missed the ball carrier. In the blindfolded condition, 68 of 81 trials (~84%) that resulted in the chaser successfully touching the ball carrier were coded and analyzed. On 13 trials, the pursuer missed the ball carrier.

Walking paths of pursuers On the cut trials, the pursuer's path after the ball carrier made a cut was analyzed as a separate path for regression analysis. Therefore, cut trials have both linear and polynomial regression analyses applied twice per trial. This affects the degrees of freedom, because straight trials have only one linear and polynomial regression analysis per trial. There were 47 sighted straight trials and 42 blindfolded straight trials (straight trials are defined as trials intentionally straight and trials on which the ball carrier was intercepted before making a 30° cut) and 31 sighted cut trials and 26 blindfolded cut trials. Linear regression analyses indicated that straight lines accounted for over 98.68% of the variance in the walking paths of the pursuers in the sighted condition (SD = .02) versus 79.41% of the variance in the blindfolded condition (SD = .22). A one-way ANOVA revealed a significant difference between conditions, $F(1, 201) = 79.95$, $p < .001$. This was a large effect, $\eta^2 = .29$. Straight lines accounted for significantly more variance in the sighted condition than in the blindfolded condition. A 2 × 2 factorial ANOVA with before/after and cut-up/cut-down as conditions found a significant main effect showing that significantly less variance was accounted for after the cut (M = .82, SD = .27) than before (M = .94, SD = .08), $F(1, 110) = 9.28$, $p = .003$. This was a small effect, $\eta^2 = .08$. We also analyzed how much variance a polynomial (one curve) fit accounted for in walking paths of the pursuers. In the sighted condition, the polynomial accounted for 99.57% of the variance in the walking paths of the pursuers (*SD* = .01) versus 93.5% of the variance in the blindfolded condition (*SD* = .13). A one-way ANOVA again revealed no difference between sighted and blindfolded conditions, $F(1, 217) = 0.10$, $p > .1$. A one-sample *t*-test comparing linear and polynomial fits and using the change in R^2 showed that polynomial fits accounted for significantly more variance than did linear fits, $t(218) = 4.84$, $p < .001$. This was a medium-sized effect, Cohen's $d = 0.5$. Thus, polynomial fits accounted for less than 1% more variance in the sighted condition and 14.09% more variance in the blindfolded condition. Representative walking path trials in the sighted condition are shown in the left panels of Fig. 5, while representative walking path trials in the blindfolded condition are shown in the left panels of Fig. 6.

Target-heading angle We measured target-heading angle at each 1/60th of a second. For the cut trials, we again divided the trial where the cut was made and calculated the target-heading angle prior to and after the cut. For all conditions, the target-heading angle was well above 0, consistent with using a CTHA. For the trials on which there was no cut, the mean target-heading angle, β, for the sighted condition was 42.74° (*SD* = 28.45°), while the mean target-heading angle, β, for the blindfolded condition was 18.93° (*SD* = 25.64°). For the trials on which the ball carrier cut, the mean target-heading angle in the sighted condition was 47.83° (*SD* = 31.62°) and 33.07° (*SD* = 23.56°) prior to the cut and after the cut, respectively. The mean target-heading angle, β, in the blindfolded condition was 17.71° (*SD* = 25.09°) and 22.81° (*SD* = 22.77°) prior to the cut and after the cut, respectively.

Change in the target-heading angle The mean change in the target-heading angle for the sighted condition was 0.08°

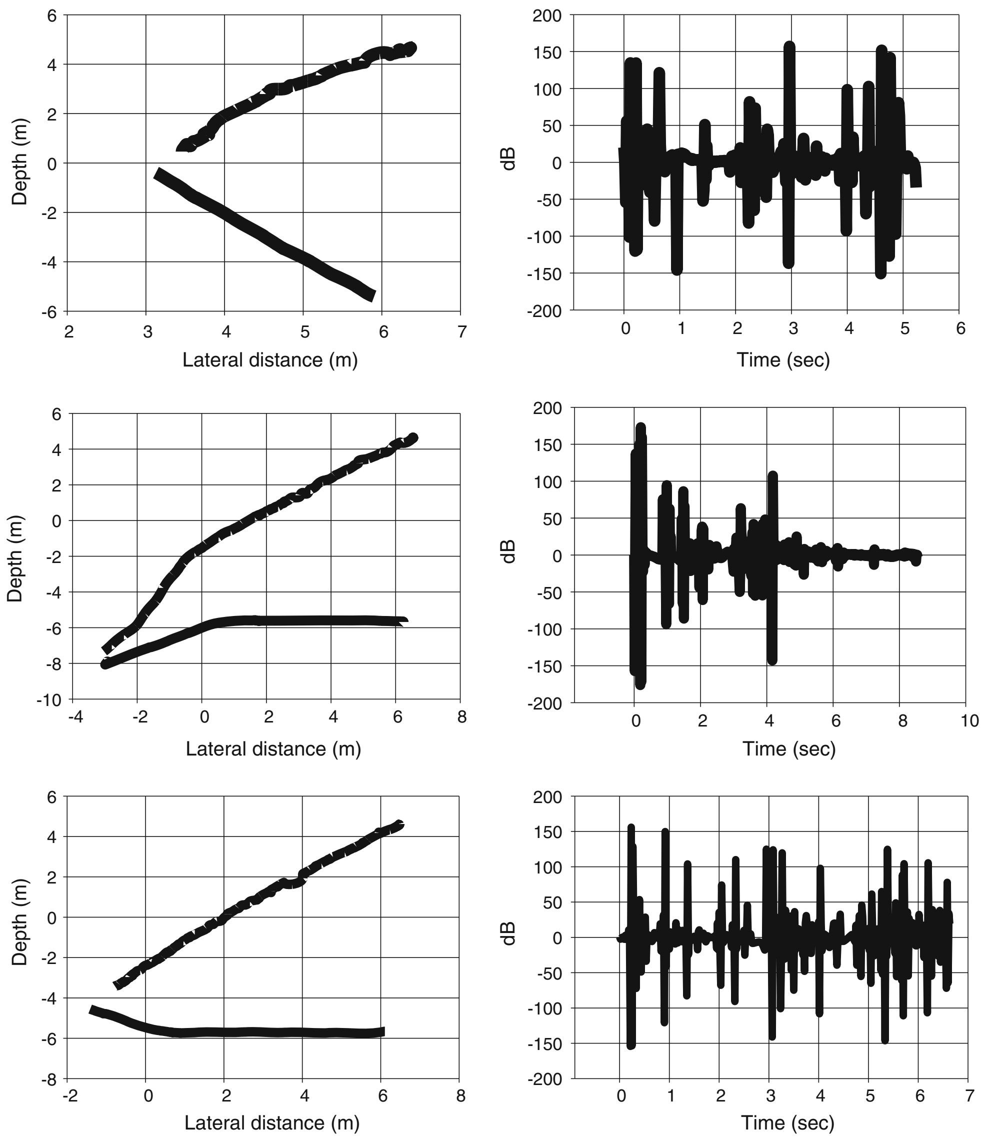


Fig. 5 Left panels: Representative walking path trials in the sighted condition. Right panels: Changes in the target-heading angle, *dβ/dt*, corresponding to the running paths shown in the left panels

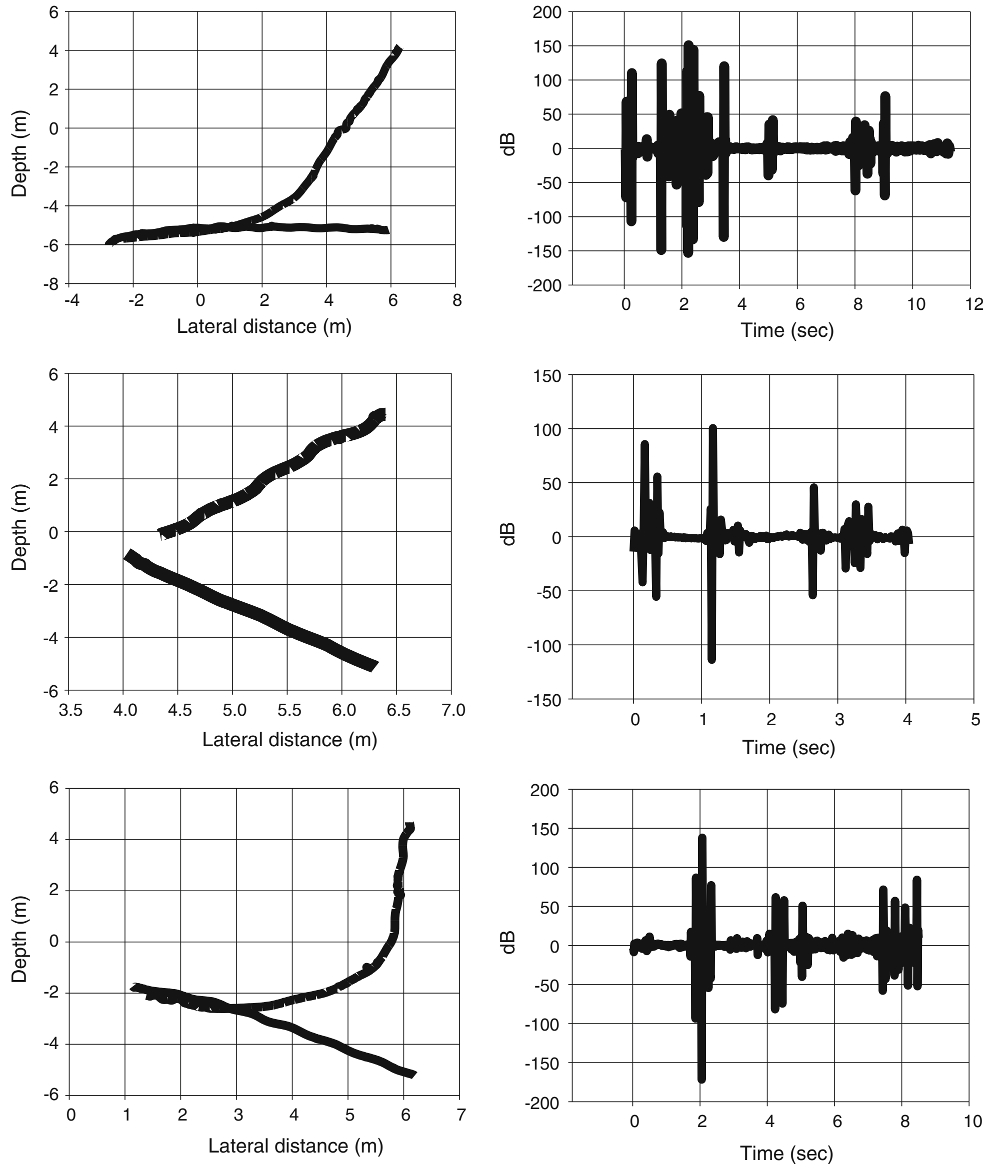


Fig. 6 Left panels: Representative walking paths in the blindfolded condition. Right panels: Changes in the target-heading angle, *dβ/dt*, corresponding to the running paths shown in the left panels

(SD = 0.18°). In order to test whether *dβ/dt* was significantly different from 0, we performed a one-sample *t*-test that showed that *dβ/dt* was not statistically different from 0, $t(28280) = 0.45$, $p > .5$. We also found that the mean change in the target-heading angle, *dβ/dt,* for the sighted condition was statistically no different from that for the blindfolded condition, $F(1, 59600) = 0.02$, $p > .5$ (blindfolded condition, $M = .11$, $SD = .14$). Plots of changes in target-heading angle over time corresponding to the walking path trials shown in Fig. 5 are shown in Fig. 6. We also found that experience did not affect the mean change in the *dβ/dt,* $F(3, 59598) = 0.04$, $p > .5$.

Change in target-heading angle precut versus postcut versus no cut Just to remind the reader, cut trials have changes in target-heading angle applied twice per trial (once precut and once postcut). This affects the degrees of freedom because straight trials have only one change in target-heading angle per trial. In order to test whether maintaining a CTHA still works when the ball carrier's trajectory deviates from a straight line and after a change in trajectory, as compared with before, we performed a 2 (vision condition: sighted/blindfolded) × 3 (cut portion: before-cut/after-cut/no-cut) factorial ANOVA. There was no main effect of cut portion, $F(2, 59596) = 0.17$, $p > .5$. Additionally, there was no difference in strategy taken before and after the cut between vision groups, since the interaction was not statistically significant, $F(2, 59596) = 0.12$, $p > .5$.

Misses There were 16 misses out of 172 trials (0.09%), 3 of which were in the sighted condition. On all 3 of these trials in the sighted condition, the ball carrier's path was 90°, and all pursuers used a CTHA strategy but were too slow. For the 13 misses in the blindfolded condition, pursuers incorporated a CTHA strategy 5 times (in 2, they used CTHA but were too slow, and in another 3, they used a combination of CTHA and pursuit), and on the other 8 trials, pursuers used only a pursuit strategy. Again, in 100% of the cases, the raters agreed as to how the misses should be categorized. Figure 7 shows graphs of misses from pursuers with varying levels of expertise and varying strategies from Experiments 1 and 2. All three left panels are from Experiment 1 from pursuers who were categorized as 4 = *I play/played often* (this could be the equivalent of playing in high school). In the top and middle left panels, the pursuer used the pure prediction strategy, and the pursuer shown in the bottom panel used a combination strategy—CTHA followed by a pursuit strategy. All three right panels are from Experiment 2 from two different pursuers who were categorized as 1 = *I have never played*. These pursuers used the pursuit strategy in all three panels.

Pursuer speeds Average pursuer speeds were 1.58 m/s (SD = 0.78) and 1.34 m/s (SD = 1.95) for the sighted and blindfolded conditions, respectively. This amounts to ~1/5th of a meter per second difference in speed.

Comparison of changes in dβ/dt, in the jogging condition of Experiment 1 with those in the walking condition of Experiment 2

In order to compare whether there was any difference across jogging and walking conditions in Experiments 1 and 2, we performed a one-way ANOVA of changes in target-heading angle, $d\beta/dt$, and found that there was no difference across conditions, $F(1, 113892) = 0.11$, $p > .5$.

Discussion

Ordinary people walking to intercept a ball carrier used a CTHA strategy. Using this strategy did not change

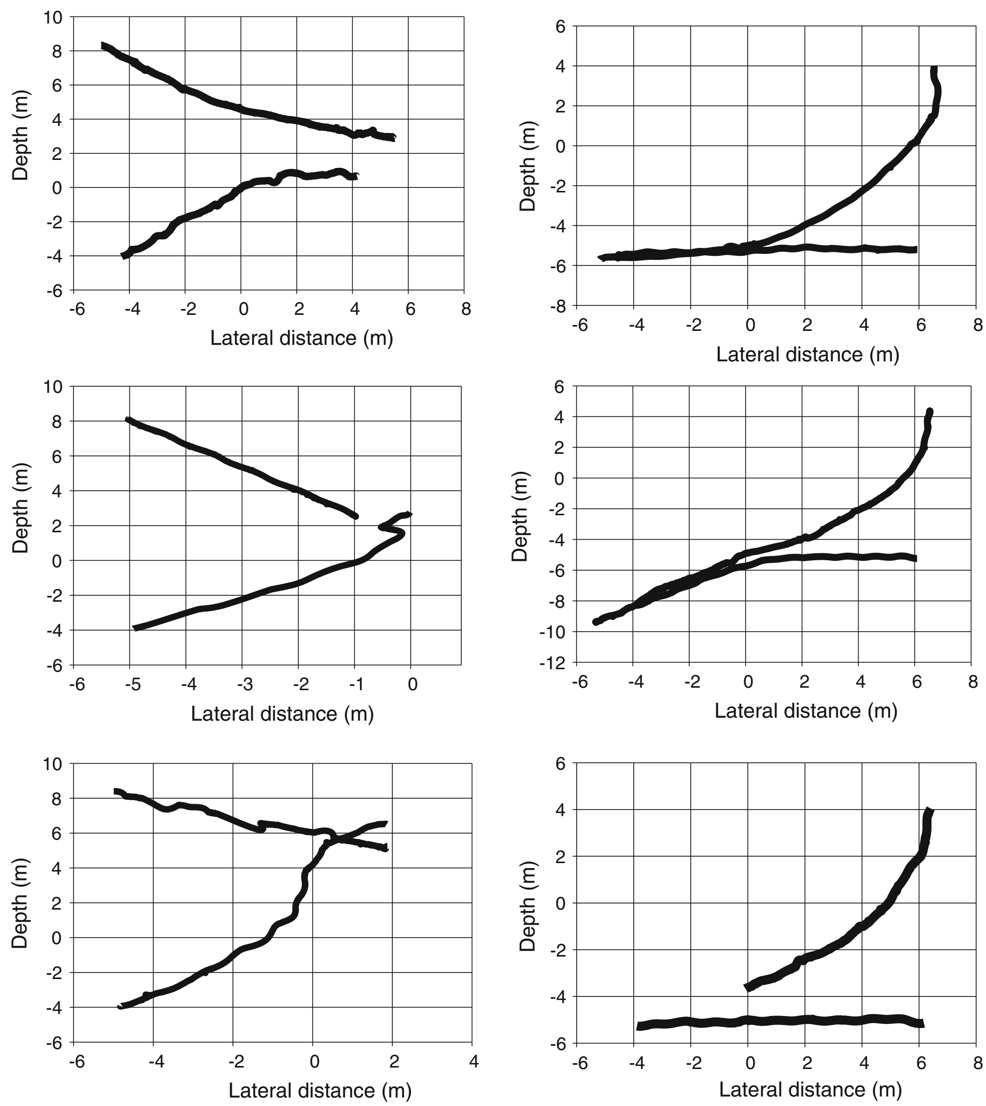


Fig. 7 Graphs of strategies used in misses when pursuers were blindfolded. Left panels: Graphs of experienced pursuers running to intercept the ball carrier. In the top and middle panels, the purser used a pure predictive strategy, whereas in the bottom panel a combination strategy was used (constant target-heading angle followed by pursuit). Right panels: Graphs of pursuers with no experience. In every case, the pursuer used a pursuit strategy

irrespective of whether the pursuers were sighted or blindfolded. Straight lines accounted for 99% of the variance in the sighted condition, and polynomial fits accounted for less than 1% more variance. Only ~79% of variance was accounted for in the blindfolded condition. Polynomial fits accounted for 14% more variance in the blindfolded condition. The biggest difference between fits that accounts for the overall difference is when ball carriers were cutting (especially when they cut down) in the blindfolded condition. We expected this because of the change in direction and also because it takes longer to change direction and to get to the right spot when walking than when jogging. However, a CTHA still followed, because the requirement of CTHA for the pursuit paths is to approximate straight lines, and accounting for ~99% of the variance in the sighted condition was enough to do this and accounting for almost 80% of the variance in the blindfolded condition was enough to do this as well. Again, the end result of the CTHA is that the change in the target-heading angle remains constant at 0, which it did in both conditions. In fact, the end result of the linear paths accounting for a difference of ~13% of the variance resulted in a change in the target-heading angle amounting to 0.03°. Thus, the CTHA strategy is robust because it works with slight deviations from the ideal situation.

General discussion

We have shown that blindfolded and sighted players use a CTHA strategy to intercept moving targets. This result occurs irrespective of sightedness, football experience, and jogging versus walking. Although we find higher interception rates for sighted trials than for blindfolded trials, this is expected given the differential thresholds for motion perception between audition and vision. For example, auditory psychophysical work on the "minimum audible movement angle" (Gertzman, 2010; Perrott & Musicant, 1981) has shown that the thresholds for the detection of auditory motion are dramatically higher than visual motion thresholds (e.g., Acheson, Cassidy, Grunfeld, Shallo-Hoffman, & Bronstein, 2001; Tynan & Sekuler, 1982). Moreover, direct comparisons of *predicted motion* in the auditory and visual modalities show greater error and higher variability in predicted auditory motion judgments than in matched visual motion judgments (Prime & Harris, 2010). Nonetheless, despite the poorer spatial resolution of the auditory system, the pursuit performance reported here is well within the limits of the system, and the mechanisms are fairly straightforward. For example, in order to aim slightly ahead of the target and maintain a constant angle so that the derivative of the angle with respect to time is equal to 0, blindfolded pursuers needed only to follow a path that kept interaural level differences constant. Thus, although the errors in auditory-only pursuit performance are higher, due to the poorer spatial resolution of the auditory modality, the pursuit strategies employed are likely the same.

These results have implications for the mechanisms that could be driving intercepting moving targets. For example, Rushton et al. (1998) found that perceived location, rather than optic flow, is the predominant cue that guides locomotion on foot, and Fajen and Warren (2007) found that the change in the target-heading angle is determined from proprioception about gaze angle with respect to the locomotor axis. One implication of our work is that although *perceived location* and *gaze angle* refer to vision in these studies, they could be interpreted more universally. Perceived location could come through either vision or audition, whereas gaze angle could be interpreted more universally as the facing direction of the head or *head-centric* coordinates, rather than retinotopic coordinates. Our work also suggests two possibilities for the representation of controlling a CTHA in order to achieve interception. First, our findings suggest that the mechanisms involved in intercepting moving targets are built to drive behavior that leads to a CTHA. This is to say that the mechanisms may be different (vision or audition, or the different brain areas and cues we use to localize moving targets) but the strategy used to intercept targets is the same. Second, while many areas of the brain may be implicated in the representation of motion perception related to guiding one toward the use of a CTHA, bilateral activation of the superior parietal lobule (SPL) has been found both when simulating self-motion forward and backward to near and far road edges and when picking up information from road edges that allows people to actively control their simulated heading direction in order to maneuver along a winding road (Billington, Field, Wilkie, & Wann, 2010; Field, Wilkie, & Wann, 2007). While the tasks are different, this suggests that the SPL may also be involved in picking up and guiding visual information critical to maintaining a CTHA. Other work shows that the purported human homologue to monkey area VIP, including the posterior parietal cortex centered on the depth of the intraparietal sulcus, is strongly activated to moving stimuli whether the stimulation is visual, tactile, or auditory in nature (Bremmer et al., 2001). Thus, it may be that in the absence of vision, similar brain areas operate in order to help achieve the same goal. Perhaps in blindfolded individuals, these mechanisms rely on polymodal motion processing areas in the brain in the absence of vision, as they do in the presence of vision.

In conclusion, the present results demonstrate that both blindfolded and sighted individuals use the same strategy of maintaining a constant target-heading angle in order to successfully achieve interception.

Author Notes Dennis M. Shaffer, Eric McManama, Charles Swank, Kahlin Kelly, and Andrew Maynor, Department of Psychology, Ohio

State University; Igor Dolgov, Department of Psychology, New Mexico State University; John Neuhoff, Department of Psychology, College of Wooster.

We would like to thank David T. Field for the suggestion of conducting Experiment 2.

References

Acheson, J. F., Cassidy, L., Grunfeld, E. A., Shallo-Hoffman, J. A., & Bronstein, A. M. (2001). Elevated visual motion detection thresholds in adults with acquired ophthalmoplegia. *British Journal of Ophthalmology, 85,* 1447–1449.

Bastin, J., Calvin, S., & Montagne, G. (2006). Muscular proprioception contributes to the control of interceptive action. *Journal of Experimental Psychology. Human Perception and Performance, 32,* 964–972.

Billington, J., Field, D. T., Wilkie, R. M., & Wann, J. P. (2010). An fMRI study of parietal cortex involvement in the visual guidance of locomotion. *Journal of Experimental Psychology. Human Perception and Performance, 36,* 1495–1507.

Bremmer, et al. (2001). Polymodal motion processing in posterior parietal and premotor Cortex: A human fMRI study strongly implies equivalencies between humans and Monkeys. *Neuron, 29,* 287–296.

Chardenon, A., Montagne, G., Buekers, M. J., & Lauent, M. (2002). The visual control of ball interception during human locomotion. *Neuroscience Letters, 334,* 13–16.

Crowell, J. A., Banks, M. S., Shenoy, K. V., & Andersen, R. A. (1998). Visual self motion perception during head turns. *Nature Neuroscience, 1,* 732–737.

Fajen, B. R., & Warren, W. H. (2003). Behavioral dynamics of steering, obstacle avoidance, and route selection. *Journal of Experimental Psychology. Human Perception and Performance, 29,* 343–362.

Fajen, B. R., & Warren, W. H. (2004). Visual guidance of intercepting a moving target on foot. *Perception, 33,* 689–715.

Fajen, B. R., & Warren, W. H. (2007). Behavioral dynamics of intercepting a moving target. *Experimental Brain Research, 180,* 303–319.

Field, D. T., Wilkie, R. M., & Wann, J. P. (2007). Neural systems in the visual control of steering. *The Journal of Neuroscience, 27,* 8002–8010.

Gertzman, S. (2010). Effects of velocity and motion-onset delay on detection and discrimination of sound motion. *Hearing Research, 246*(2008), 44–51.

Lanchester, B. S., & Mark, R. F. (1975). Pursuit and prediction in the tracking of moving food by a teleost fish (Acanthaluteres spilomelanurus). *Journal of Experimental Psychology. General, 63,* 627–645.

Land, M. F., & Collett, T. S. (1974). Chasing behaviour of houseflies (Fannia canicularis). A description and analysis. *Journal of Comparative Physiology, 89,* 331–357.

Lenoir, M., Musch, E., Janssens, M., Thiery, E., & Uyttenhove, J. (1999). Intercepting moving objects during self-motion. *Journal of Motor Behavior, 31,* 55–67.

Perrott, D. R., & Musicant, A. D. (1981). Dynamic minimum audible angle: Binaural spatial acuity with moving sound sources. *The Journal of Auditory Research, 21*(4), 287–295.

Prime, S. L., & Harris, L. R. (2010). Predicting the position of moving audiovisual stimuli. *Experimental Brain Research, 203*(2), 249–260.

Rossel, S., Corlija, J., & Schuster, S. (2002). Predicting three-dimensional target motion: How archer fish determine where to catch their dislodged prey. *The Journal of Experimental Biology, 205,* 3321–3326.

Rushton, S. K., Harris, J. M., Lloyd, M. R., & Wann, J. P. (1998). Guidance of locomotion on foot use perceived target location rather than optic flow. *Current Biology, 8,* 1191–1194.

Shaffer, D. M., & Gregory, T. B. (2009). How football players determine where to run to tackle other players: A mathematical and psychological description and analysis. *The Open Sports Sciences Journal, 2,* 29–36.

Tynan, P. D., & Sekuler, R. (1982). Motion processing in peripheral vision: Reaction time and perceived velocity. *Vision Research, 22,* 61–82.

Warren, W. H. (1998). Perception of heading is a brain in the neck. *Nature Neuroscience, 1,* 647–649.

Wilkie, R. M., & Wann, J. P. (2005). The role of visual and nonvisual information in The control of locomotion. *Journal of Experimental Psychology. Human Perception and Performance, 31,* 901–911.

Wohl, S., & Schuster, S. (2006). Hunting archer fish match their take-off speed to distance from the future point of catch. *The Journal of Experimental Biology, 209,* 141–151.