Perceiving a discontinuity in motion

Dylan Nieman

Division of Biology and Computation and Neural Systems Program,
California Institute of Technology, Pasadena, CA, USA, &
Department of Surgery, University of Rochester,
Rochester, NY, USA

Bhavin R. Sheth

Department of Electrical and Computer Engineering,
University of Houston, Houston, TX, USA, &
Center for NeuroEngineering and Cognitive Sciences,
University of Houston, Houston, TX, USA

Shinsuke Shimojo

Division of Biology and Computation and Neural Systems Program,
California Institute of Technology, Pasadena, CA, USA, &
JST.ERATO Shimojo Implicit Brain Function Project,
NTT Communication Science Laboratories,
Atsugi, Kanagawa, Japan

Studies have shown that the position of a target stimulus is misperceived owing to ongoing motion. Although static forces (fixation, landmarks) affect perceived position, motion remains the overwhelming force driving estimates of position. Motion endpoint estimates biased in the direction of motion are perceptual signatures of motion's dominant role in localization. We sought conditions in which static forces exert the predominant influence over perceived position: stimulus displays for which target position is perceived backward relative to motion. We used a target that moved diagonally with constant speed, abruptly turned 90° and continued at constant speed; observers localized the discontinuity. This yielded a previously undescribed effect, "turn-point shift," the tendency of observers to estimate the position of orthogonal direction change backward relative to subsequent motion direction. Display and mislocalization direction differ from past studies. Static forces (foveal attraction, repulsion by subsequently occupied spatial positions) were found to be responsible. Delayed turn-point estimates, reconstructed from probing the entire trajectory, shifted the horizontal coordinate forward in the direction of motion. This implies more than one percept of turn-point position. As various estimates of turn-point position arise at different times, under different task demands, the perceptual system does not necessarily resolve conflicts between them.

Keywords: motion-2D, spatial vision, eye movements

Citation: Nieman, D., Sheth, B. R., & Shimojo, S. (2010). Perceiving a discontinuity in motion. *Journal of Vision, 10*(6):9, 1–23, http://www.journalofvision.org/content/10/6/9, doi:10.1167/10.6.9.

Introduction

What causes a motion stimulus that is smoothly varying in space–time to be perceived as a series of distinct elements or an integrated whole? Are there any conditions that could cause a stimulus, or a part of it, that is otherwise perceived holistically to be perceived piecemeal or segmented from the rest? These fundamental questions in perception have a rich background in psychology arising in part from an early conflict between structuralism on the one hand (Palmer, 1999; Titchener, 1898; Wundt, 1884) and Gestaltism (Koffka, 1935; Palmer, 1999) on the other. Structuralists proclaimed that perception arises from a process in which sensory experiences are concatenations of sensory atoms, or primitive, indivisible elements of experience in a given sense. In contrast, Gestaltists argued that perception consists of wholes that cannot be reduced to parts or the sum of parts; further, they identified properties in perception that were not shared by any of the component parts but that emerged from relationships among them.

Motion is an example of a percept that emerges when discrete positions across space and time combine in the mind to yield an indivisible whole. Studies suggest that the emergence of a motion gestalt is not instantaneous (Kanai, Sheth, & Shimojo, 2007). Rather, the moving stimulus is initially perceived as a time series of discrete, potentially isolatable frames or snapshots; 200–300 ms after the stimulus begins moving, the stimulus crystallizes into an indivisible gestalt. The issue addressed in the present study is, in many ways, its converse. Here, we examine the experimental conditions under which a frame of a stimulus, which has been moving steadily for over a second, is integrated with the rest of the trajectory but, under task demand, can be isolated perceptually and displaced away from the motion trajectory.

To address this issue, we devised a moving target stimulus that travels at uniform speed, abruptly changes

direction, and continues moving after the direction change with speed unchanged; we measured the percept of the spatial position of the change in direction, henceforth termed the turn-point, with respect to the target's motion trajectory.

It is important to distinguish between at least two possible sets of positional error. The complete (pre- and post-turn, see Figure 1a) trajectory of the target can be thought of as either 1) a single, continuous gestalt that experiences a transient change in feature (its direction), or
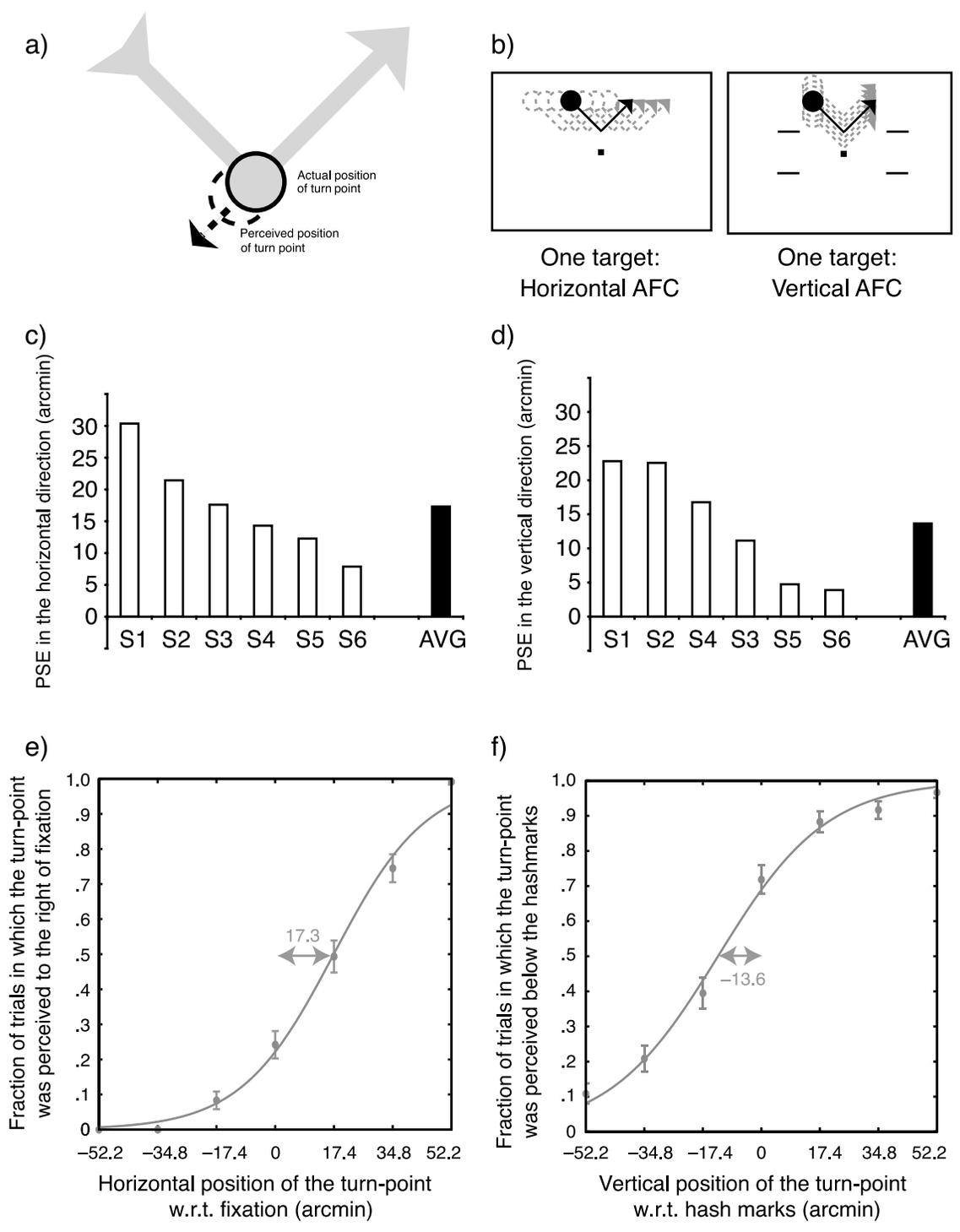

Figure 1. The turn-point shift for a single target: a) Schematic representation of the perceived effect. b) Schematics of the experimental displays. c, d) Points of Subjective Equality for each observer. e, f) Psychometric curves for pooled observer data along the horizontal and vertical directions. Error bars are one *SEM*.

2) a juxtaposition of two distinct, orthogonal trajectories, the first terminating and the second originating at the turn.

If the target is represented in the first way delineated above, we might imagine that there is either no systematic bias in the positional error, or that the percept of the turn gets delayed with the result that the turn-point is perceived forward somewhere along the post-turn trajectory (Ogmen, Patel, Bedell, & Camuz, 2004; Patel, Ogmen, Bedell, & Sampath, 2000).

If the target is represented in the second way, the location of the turn could be influenced by other forces besides motion whose signature could be a perceptual positional bias *away* from the ongoing motion direction. Studies (Moore & Enns, 2004) suggest that an abrupt and large change in an object feature can cause the generation of a second object representation: if the abrupt direction change or turn is sufficient in this regard, we may expect the motion trajectory illustrated in Figure 1a to behave as two distinct objects or trajectories that happen to coincide at the position of the turn. This is equivalent to thinking of the target in the second manner delineated above. In this case, the perception of the position of the turn may be shifted as an effect of the termination of the initial trajectory, an effect of the origination of the second, or as somewhat shifted or displaced away from both legs of the trajectory altogether. Thus, a displacement in the percept of the position of the turn from its position within the trajectory is a marker of the turn as a distinct perceptual entity. The turn does not appear to be displaced perceptually from the rest of the trajectory during ongoing motion; this would imply that a new (biased) percept of the turn position is formed.

Experiment 1a: The turn-point shift: Single target

Observers viewed a small, circular, diagonally moving target on a computer screen make an abrupt 90 degree turn. On each trial, the target appeared in the upper left quadrant and moved down and to the right towards the center of the screen until it reached the midline when it would abruptly change direction and move up and to the right, towards the upper right corner of the screen. Observers were asked to fixate on a small dot in the center of the screen (below the turn-point of the target) and judge the position of the turn in either the horizontal direction with respect to the fixation point, or in the vertical direction with respect to nearby hash marks.

Participants

Six naive, unpaid observers with normal or corrected to normal vision participated.

Apparatus

All experiments were performed on a Windows PC computer connected to a 19″ monitor with a refresh rate of 60 Hz and a resolution of 800 × 600 pixels. Viewing distance was 57 cm, such that 20.7 pixels subtended 1 degree of visual angle. Software was scripted in Matlab utilizing the psychophysics toolbox (Brainard, 1997; Pelli, 1997). The experimental room was dimly lit (0.10 cd/m²) and the monitor frame and experimental surroundings were visible. The apparatus was the same in all experiments.

Stimuli

On each trial, a circular target 0.87 deg in diameter appeared to the upper left of fixation and moved diagonally down and to the right at a 45 deg angle and a speed of 12.3 deg/sec for 1090 ms and then changed direction and moved up and to the right at a 45 deg angle and the same speed for another 1090 ms (Figure 1a). A central fixation point 0.10 × 0.10 deg was constantly visible. On blocks of trials in which the horizontal position of the turn-point was tested, the target appeared at one of seven horizontally spaced locations such that the turn-point occurred 3.4 deg above the fixation point either directly aligned or 0.3, 0.6, or 0.9 deg to the right or left. On trial blocks in which the vertical position of the turning point was tested, small horizontal hash marks 0.10 × 3.9 deg were visible 3.4 deg above and 4.8 deg to the right and left of the fixation point. On these trials, the target appeared at one of seven vertically spaced locations such that the turn-point occurred horizontally centered above the fixation point and either directly aligned with or 0.3, 0.6, or 0.9 deg above or below the hash marks. The fixation point and all targets were presented in white (83.5 cd/m²) against a black background (0.215 cd/m²).

Task

Observers were familiarized with the stimulus display and response keys and then asked to judge, in a binary choice task, whether the turn-point of the target appeared to the left or right of fixation in horizontal test blocks, and above or below the visible hash marks in vertical test blocks. They were instructed to hold their gaze on the central fixation point throughout the experiment. Target position was randomized across trials (140 = 20 trials/position × 7 positions).

Analysis

Horizontal and vertical displacements of the perceived turn-point were probed and analyzed separately. First, we

pooled all the individual percent-response data at each turn-point location, as individual subjects had extremely similar levels of bias and sensitivity (slopes) in their individual curves (see Figures 1c and 1d). The pooled responses were then fitted with a psychometric curve:

$$F(x) = 0.5 + \frac{(a + bx)}{2\sqrt{1 + (a + bx)^2}}. \qquad (1)$$

Free parameters a and b were estimated by a least-squares criterion and the point of subjective equality (PSE) was obtained as $(-a/b)$. Thus each PSE represented the displacement necessary for the perceived turn-point to be horizontally aligned with the fixation point or vertically aligned with the hash marks. Positive values correspond to leftward and upward displacement of the turn-point, both of which, in turn, correspond to a rightward shift in the PSEs of the respective psychometric curves. For statistical significance, the PSEs of individual subjects were obtained and then analyzed using a two-tailed, unpaired t-test.

Results

In the horizontal direction, the average perceived turn-point of the target was 17.3 ± 4.8 arcmin to the left of (behind) the actual turn-point (Figure 1e; $t(5) = 3.63$, $p = 0.015$). In the vertical direction, the average perceived turn-point of the target was 13.6 ± 4.3 arcmin below the actual turn-point (Figure 1f; $t(5) = 3.20$, $p = 0.024$). The size of the effect was not dramatic, but was nonetheless significant in both dimensions (note that the turn-point was presented in the observer's near-foveal vision where visual acuity is high); furthermore, the effect was remarkably consistent and in the same direction for all our observers (Figures 1c and 1d).

Discussion

Along both dimensions, i.e. horizontal along which motion was uniform throughout and vertical along which direction reversed half-way during the motion, the perceived position of the turn-point was shifted from veridical. The error was not random, but systematic and backward along the post-turn part of the trajectory. Nonetheless, the turn-point was perceptually inseparable from the motion trajectory and integrated into its gestalt. Thus, the turn-point seems to be perceived as part and parcel of a motion trajectory as well as backwards along the post-turn part of the trajectory. Additional experiments described below will explore the limits of the effect, distinguish it from other phenomena in the literature,

explore the role of attention, and propose a set of candidate mechanisms to account for the effect.

Experiment 1b: The upside-down case

In order to explore the generality of the above finding, the experiment was repeated with the target's trajectory rotated 180 degrees about the fixation point (appearing in the lower right quadrant of the screen, moving up-left, turning abruptly near the center, and then moving down-left).

Participants

The same six observers from Experiment 1a participated.

Stimuli

The display was the same as in Experiment 1a, but with the target appearing to the lower right of fixation, moving diagonally up and to the left at a 45 deg angle and a speed of 12.3 deg/sec for 1090 ms, then changing direction and moving down and to the left at a 45 deg angle and the same speed for another 1090 ms. On trial blocks in which the vertical position of the turning point was tested, small horizontal hash marks 0.10 × 3.9 deg were visible 3.4 deg below and 4.8 deg to the right and left of the fixation point.

Task

The task was the same as in Experiment 1a. Each observer ran a total of 140 (=20 trials/position × 7 positions) trials.

Results

The results were analogous to those in Experiment 1a. Displacement of the perceived turn-point was backwards along the eventual post-turn trajectory 16.3 ± 4.3 arcmin to the right ($t(5) = 3.77$, $p = 0.013$) of the true turn-point and 15.7 ± 4.5 arcmin above ($t(5) = 3.47$, $p = 0.018$).

Discussion

Experiments 1a and 1b together suggest that regardless of the absolute direction of stimulus motion, the turn-point is perceived *behind* its true position along the direction of the post-turn trajectory. In both experiments, the perceived vertical position of the turn is biased towards fixation, which, at least on the surface, is in line with earlier studies

that found that target position is biased towards salient markers in space such as fixation (Helmholtz, 1866; Mateeff & Gourevich, 1983; Sheth & Shimojo, 2001). We will be examining this issue more directly in Experiment 8.

Experiment 1c: Two targets

The displays from Experiments 1a and 1b were combined in order to find out if the turn-point shift was sensitive to the choice of stimulus configuration and to determine if attention has a governing or modulatory role. The display contained two targets—one located above the fixation point moving from left to right, and a second located below the fixation point moving from right to left (see Figure 2a); both targets changed respective vertical directions simultaneously. In this configuration, there were at least two possible predicted outcomes. One possibility was that the presence of an additional target would provide an added frame of reference, improving the accuracy of the perception of the turn and reducing or perhaps even eliminating the turn-point shift. An alternative possibility, however, comes from considering the turn-point shift as a function of attention. If, subsequent to the moment of the turn, attention must shift from the smoothly moving target back to the perceived position of the turn in order to judge its location, then the magnitude of the turn-point shift may be a function of the time delay in executing the attentional shift. In this situation, if two targets compete for and place greater strain on the resources of attention, the effect may be greater than (potentially double) that observed in Experiment 1a or 1b.

Observers were presented with two targets, one above the fixation point, exactly as in Experiment 1a, the other similar but rotated 180 deg about the fixation point (thus below fixation, moving from down right towards fixation and then turning abruptly towards down-left, as in Experiment 1b). Subjects were instructed to attend both targets, and compare the positions of the two turn-points.

Participants

The same six observers from Experiments 1a and 1b participated.

Stimuli

The display was the same as in Experiment 1a, but with the addition of a second target, also 0.87 deg in diameter (appearing to the lower right of fixation, moving diagonally up and to the left at a 45 deg angle and a speed of 12.3 deg/sec for 1090 ms, then changing direction and moving down and to the left at a 45 deg angle and the same speed for another 1090 ms. At all times, the position of the second target was a point reflection of the position

of the first about the fixation point. As a result, both targets changed directions synchronously.

Task

Observers were asked to judge whether the turn-point of the top target appeared to the left or right of the bottom target in horizontal test blocks. Otherwise the task was the same as in Experiment 1a. Each observer ran a total of 140 (=20 trials/position × 7 positions) trials.

Results

In the horizontal direction, the group mean perceived turn-point was 16.0 ± 5.8 arcmin behind the true position (Figure 2b); the group mean error in the estimated position was significantly different from zero, or veridical perception ($t(5) = 2.76$, $p = 0.040$), but not significantly different from that of the single target case ($t(5) = 0.50$, $p = 0.64$, paired). In the vertical direction, the mean perceived turn-point of the top target was 15.1 ± 5.3 arcmin below the true position (Figure 2c). Similar to the error in the horizontal direction, the error in the vertical direction was also significantly different from zero ($t(5) = 2.85$, $p = 0.036$) and was not significantly different from the single target case ($t(5) = 0.56$, $p = 0.60$, paired) as well.

Discussion

The magnitude of the turn-point shift was statistically indistinguishable whether one or two targets were used. Attending to a second target below the fixation point and localizing the turn-points of both targets for comparison purposes did little to modulate the effect. Interestingly, the paradigm and results, which were presented earlier (Nieman, Sheth, & Shimojo, 2005, 2006), have since been applied in judging the accuracy of line calls of referees in tennis matches (Whitney, Wurnitsch, Hontiveros, & Louie, 2008). Of importance to the present purposes, the results of Experiment 1c suggest that the role of attention in producing the turn-point shift is limited, and attention may have only a modulatory role. In the following experiment, we use a cueing paradigm to examine more directly the role of attention and the observer's perceptual interpretation of the turn-point.

Experiment 2a: Visual cue

To obtain some insight on the role of attention in the turn-point shift, we added an attentional cue and observed how it affected the accuracy of the positional error. In the first experiment, we briefly flashed a cue either simultaneous with the turn or just prior (50 ms) to it.
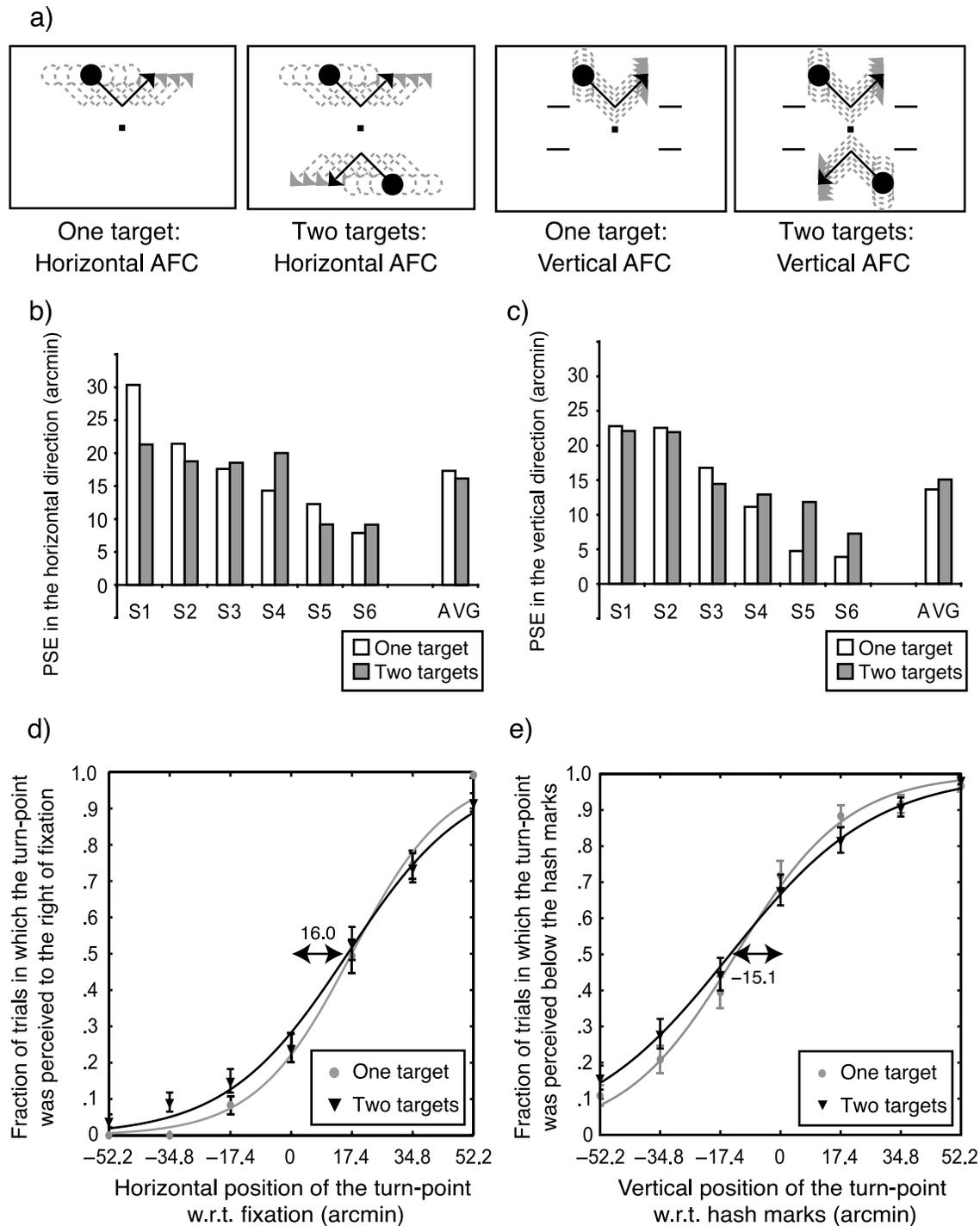
Figure 2. The turn-point shift for one vs. two targets: a) Schematics of the experimental displays. b, c) Effect magnitudes for each individual observer along the horizontal (b) and vertical (c) directions. e, f) Psychometric curves for the pooled observer data along the horizontal and vertical directions. The arrow represents the size of the effect in the two target case. Single-target data is shown in gray for comparison. Error bars are one *SEM*.

Participants

Ten naive, unpaid observers with normal or corrected to normal vision participated.

Stimuli

The stimuli in the experiment were the same as in Experiment 1a, with the exception that a visual cue

stimulus, horizontally aligned with the fixation point, was flashed for 17 ms starting from the time of the turn, or 50 ms before the turn (Figure 3a). In different blocks of trials, the cue appeared either 3.4 deg below the fixation point, or 3.4 deg above the turn-point.

Task

Observers had to judge the horizontal position of the turn-point of the target with respect to the fixation point. They were instructed to ignore the flashed visual cue.
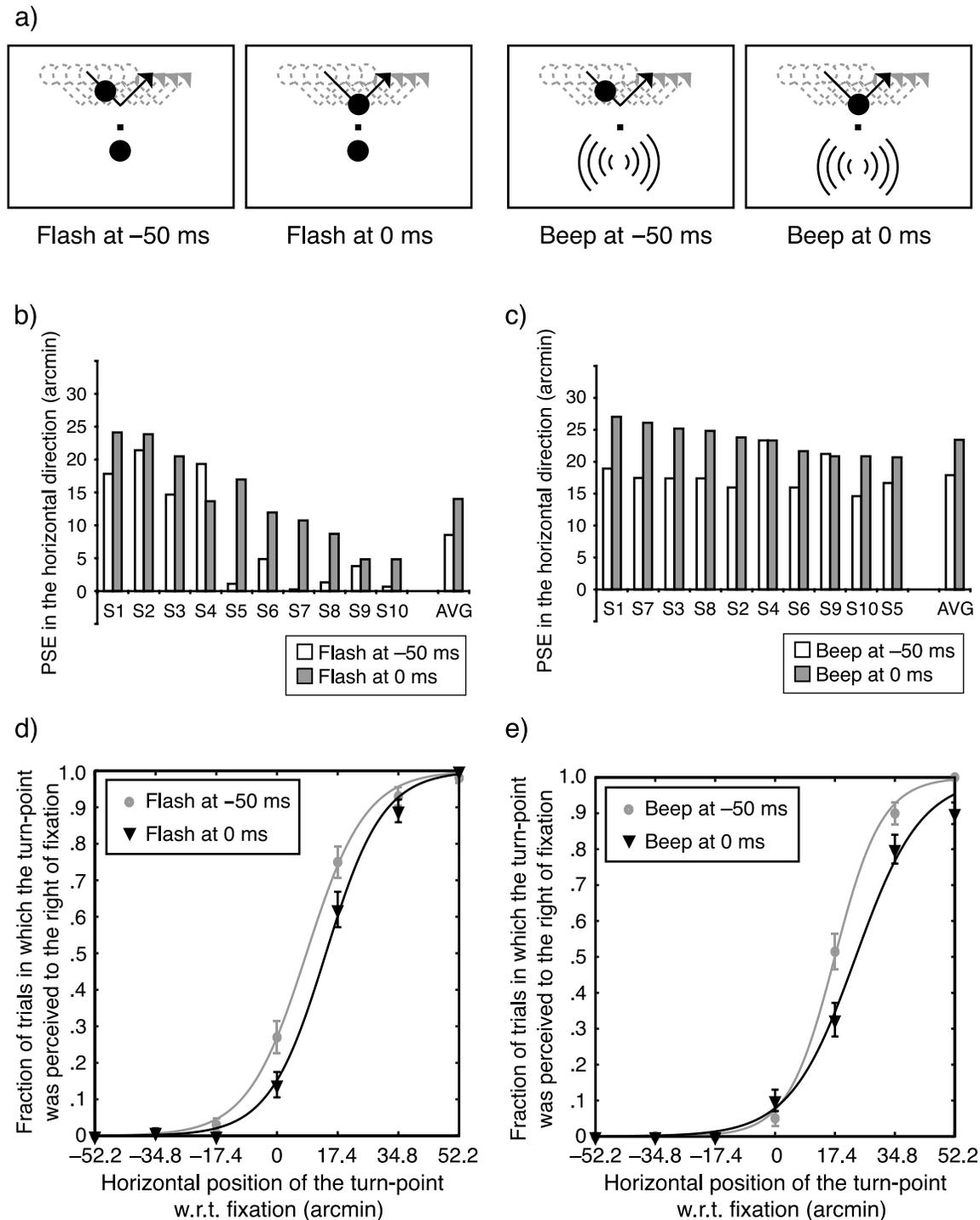

Figure 3. Modulation of the turn-point shift by a transient event prior to the turn. a) Schematics of the experimental displays. b, c) Effect magnitude for each individual observer in the visual (b) and auditory (c) flash conditions. d, e) Pooled observer data and optimal least-squares psychometric curve fits in the visual (d) and auditory (e) flash conditions. Error bars are one *SEM*.

Each observer ran a total of 280 (=20 trials/position/cue time × 7 positions × 2 cue times) trials.

Results

Results of both visual cue positions were statistically indistinguishable ($t(9) = 0.16$, $p = 0.88$, paired); for convenience, pooled results are discussed here. In the case of the visual cue flashed at the moment of the turn, the perceived position of the turn-point was 14.0 ± 2.2 arcmin to the left of the actual turn-point (Figure 3b); the magnitude was comparable to that (16.0 ± 5.8 arcmin) in the original from Experiment 1a ($t(6.47) = 0.381$, $p = 0.72$, heteroscedastic t-test; degrees of freedom were calculated using the Welch-Satterthwaite equation (Satterthwaite, 1946)). In the case of the visual cue flashed 50 ms prior to the turn, the perceived position of the turn-point was 8.5 ± 2.7 arcmin to the left of the actual (Figure 3b). The effect was substantially (40% decrease) and significantly smaller than that observed with the synchronous cue ($t(9) = 3.04$, $p = 0.014$, paired) but was significant nonetheless ($t(9) = 3.1$, $p = 0.013$).

Discussion

When a visual flash cued the turn at the same moment as the turn, the size of the turn-point shift was not affected in a significant way. In comparison, when the flash cued the turn 50 ms before the turn, the turn-point shift was significantly reduced. Thus, a cue occurring no more than 50 ms before the turn can have a significant effect on its positional accuracy, which suggests that processing the turn and determining its position in space takes time and pre-cueing the observer to the moment of the turn reduces positional error.

In addition to alerting the observer to the moment of the turn, the visual cue happens to have a discrete spatial address close to the turn-point. Thus, the visual flash serves as both a temporal cue and a spatial one. The spatial cue may serve as a frame of reference, thus improving accuracy and minimizing the turn-point shift, or as an added burden on attention, possibly degrading performance on the task. Arguably, a stimulus that cues the moment of the turn but has no spatial extent does not provide spatial reference for the location of the turn, and will therefore be less potent in reducing the magnitude of the turn-point shift. An auditory stimulus that has no discrete spatial address is just such a cue (Sheth & Shimojo, 2004).

Experiment 2b: Cross-modal auditory cue

We used a transient auditory cue, instead of a visual flash. On the basis of the arguments above, we propose that the effect with the sound will be larger than that with the flash.

Participants

The same ten observers from Experiment 2a participated.

Stimuli

The stimuli were the same as those in Experiment 1, except that observers wore headphones and a 400 Hz pure tone of 50 ms duration was played simultaneously and with equal intensity in both ears either at the moment of the turn or 50 ms before the turn on separate but interleaved trials (Figure 3a). The auditory stimulus had no discrete location.

Task

Observers had to judge the position of the turn-point of the target with respect to the fixation point. They were instructed to ignore the transient auditory cue. As in the visual cue experiment, each observer ran 280 (=20 trials/position/cue time × 7 positions × 2 cue times) trials total.

Results

On trials in which the auditory cue occurred 50 ms before the turn, the perceived position of the turn-point was 17.9 ± 2.5 arcmin to the left of the actual (Figure 3c); as predicted above, the effect was larger than that with a visual cue from the previous experiment but was not significantly different from the original no-cue effect from Experiment 1a ($t(6.90) = 0.347$, $p = 0.74$, heteroscedastic t-test). On trials in which the auditory cue was synchronous with the turn, the perceived position of the turn-point was 23.4 ± 2.2 arcmin to the left of the actual (Figure 3c), which was significantly larger than that obtained with the asynchronous auditory cue ($t(9) = 5.31$; $p = 0.0005$, paired). Thus, the presentation of a transient, auditory cue at the moment of the turn increased the turn-point shift, but presentation of the same cue before the turn had little effect.

Discussion

In general, the abrupt presentation of a cue at or around the moment and location of the turn guides the observer's attention in space and time. Experiments 2a and 2b combined show that an attentional cue can reduce but not eliminate the turn-point shift (Experiment 2a, flash

50 ms before the turn), enhance it (Experiment 2b, sound synchronous with the turn), or have little impact (Experiment 2a, flash at the moment of the turn; Experiment 2b: sound 50 ms before the turn). These findings suggest that while attention can modulate the turn-point shift, it cannot eliminate the effect entirely, and that its effect, across cue types and timings, on the turn-point shift is not in a uniform direction. The heterogeneity of outcomes obtained with cueing bolsters the proposal that attention is not the principal mechanism responsible for the turn-point effect.

Experiment 3: Eye movement control

The focus of attention is generally directed toward the center of gaze. Thus, although attention is not likely to govern the turn-point shift, eye position might. That is to say, the effect may be caused by mislocalization due to eye position or eye movement. Observers were asked to maintain fixation on a central point, but small, unintentional deviations could have biased the perceived position of the turn-point. For instance, if a subject's eyes drifted slightly to the left of fixation prior to the turn, a turn-point centered with respect to the fixation marker might appear in the right-sided visual field and would likely be judged to be right-shifted. As an alternate but similarly confounding possibility, if the instant of the turn caused the observer to execute a saccade in order to re-center their gaze, that eye movement would shift the coordinate frame of the perceived turn-point. If that coordinate frame shift were less than perfect, i.e. with gain less than 1.0 with respect to the actual magnitude of the saccade, the shift in retinal position of the turn point would be insufficient to compensate for the eye movement and the perceived position of the turn-point would be biased in the direction of the saccade.

We repeated the basic effect, monitoring eye position in order to ensure that observers maintained fixation on the fixation marker, and to see whether there was any systematic variation in eye position associated with turn point perception or observer response.

Participants

Two of the observers from Experiment 1 participated.

Apparatus

Eye tracking was performed using a head-mounted Eyelink II system (SR Research, Inc.) installed on a computer, which communicated directly with the experimental or display computer. Experimental display software was scripted in Matlab utilizing the Eyelink Toolbox (Cornelissen, Peters, & Palmer, 2002).

Stimuli

The stimuli in this experiment were the same as those in Experiment 1a.

Task

The task was the same as in Experiment 1a. As in Experiment 1a, each observer ran 140 (=20 trials/position × 7 positions) trials total.

Analysis

Prior to the start of each experimental block, the eye tracker was calibrated for both eyes, and the eye which provided the most accurate calibration result was tracked throughout the experiment. Eye position was recorded at 2 ms sample intervals throughout each trial. Data for each trial were then analyzed using custom code in Matlab, looking at the average eye position in the 100 ms before and after the occurrence of the turn. In conducting statistical tests for this experiment, each individual trial constituted a data point rather than the more rigorous statistical measure of considering each individual observer as a data point, as we used in Experiment 1; this allowed us to test for small, subtle results.

Results

In the 100–0 ms before the turn, average eye position was 2.2 ± 1.0 arcmin to the left of the fixation point for trials in which observers eventually responded left, and 0.56 ± 1.47 arcmin to the right of the fixation point for trials in which they eventually responded right (Figure 4a). The difference in eye position between the two responses was not significant ($t(278) = 1.55$; $p = 0.122$). Moreover, the direction of the deviation from fixation is opposite from what we would predict, if deviation from fixation alone were responsible for this effect. In the 0–100 ms immediately following the turn, average eye position was 1.49 ± 1.0 arcmin to the left of the fixation point for trials in which observers eventually responded left, a shift of 0.71 arcmin rightward from the 100–0 ms before the turn, and 1.69 ± 1.48 arcmin to the right of the fixation point for trials in which subjects eventually responded right, a shift of 1.13 arcmin rightward from the 100–0 ms before the turn (Figure 4b). In this case observers made rightward saccades, on average, regardless of their response.

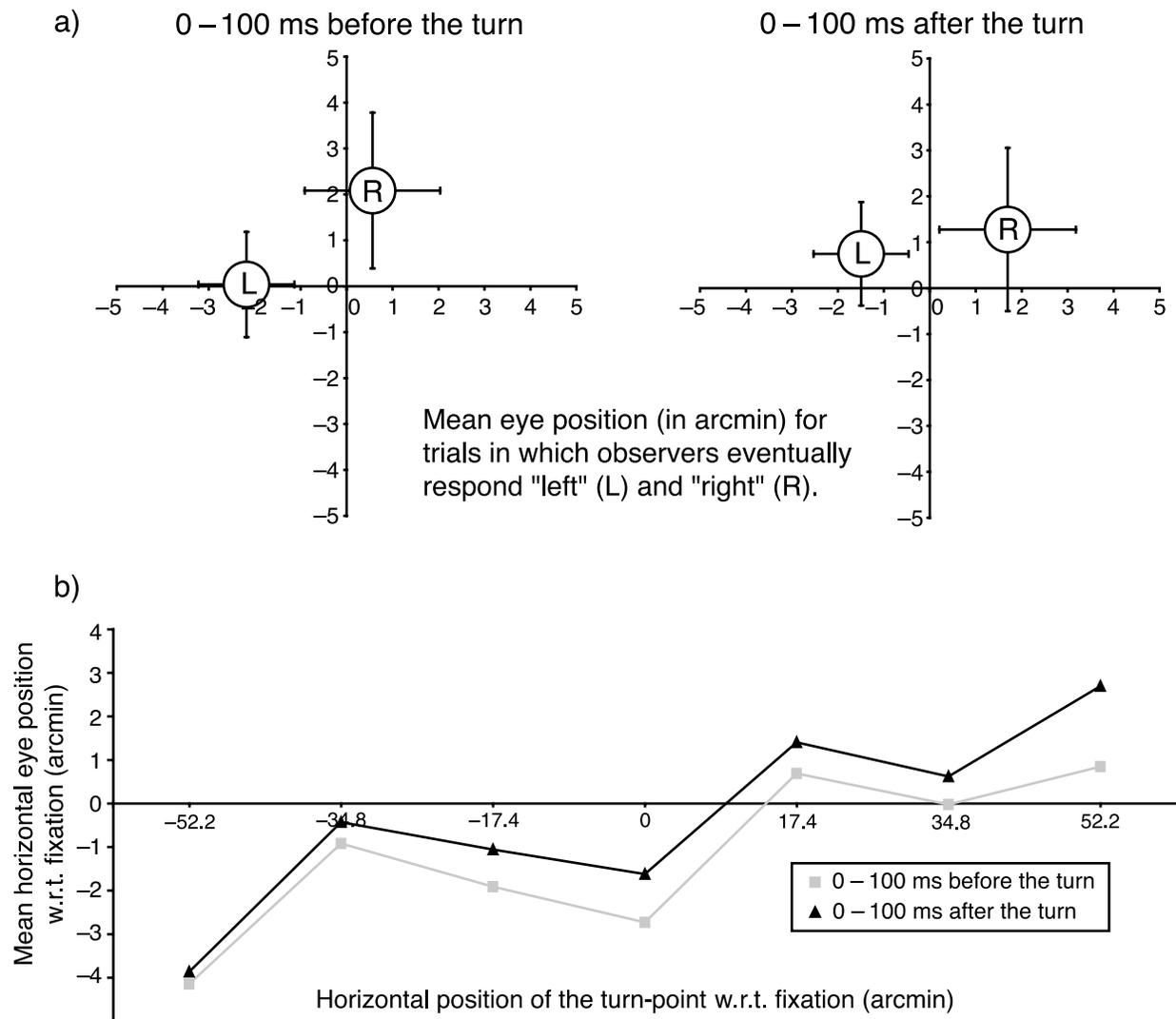Figure 4. Eye movement control. a) Mean ± *SEM* eye position with respect to fixation −100–0 ms before and 0–100 ms after the turn, classified according to eventual response. b) Mean ± *SEM* horizontal eye position with respect to fixation before and after the turn based upon the actual position of the turn point.

Rightward saccades with incomplete gain of the retinal coordinate compensation would shift the perceived position of the turn-point to the right. Again, this is opposite to the direction in which the turn-point appears shifted. On a final note, the misalignment in eye position from the actual turn point either before or after the turn was an order of magnitude smaller than that of the perceived shift in turn-point location (17.3 arcmin on average, see Experiment 1).

Discussion

The pre- and post-turn eye position data suggest that the position of the eye immediately before or right after the turn-point, namely around the time the observer's judgment of turn-point position could have been affected by sensorimotor influences, had little influence on the perceived position of the turn-point. Therefore, we can state that it is likely that the turn-point shift is a perceptual effect, not a sensorimotor one.

Experiment 4: Probing the trajectory

To further study the perceptual nature of the effect, it is important to establish the perceived path of the moving target and not just the turn-point alone. To this end, we repeated the conditions of Experiment 1a with the addition of a small probe, which flashed after the disappearance of the moving target. Observers had to judge the position of the probe relative to the path the moving target had taken. It is important to note that the probe flashed following the

target's motion, and therefore, the observer's positional judgments were now based on a representation of the trajectory stored in his or her iconic or working memory.

Participants

Four naive, unpaid observers with normal or corrected to normal vision who had participated in Experiment 1, participated here.

Stimuli

The stimuli were the same as those in Experiment 1a, except that 17 ms after the disappearance of the moving target a white (83.5 cd/m^2), circular probe 0.19 deg in diameter would appear and persist near the previously traced path of the target. In eight separate blocks, the moving target's path was probed 9.8, 6.6, 3.3, and 1.6 degrees prior to the turn-point (25%, 50%, 75%, and 87.5% of the way along the pre-turn path), and 1.6, 3.3, 6.6, and 9.8 degrees subsequent to the turn (12.5%, 25%, 50% and 75% of the way along the post-turn path). Within each block the probe would appear at one of seven positions, either directly along the path of the target or 0.41, 0.82, or 1.22 degrees orthogonally displaced from it (Figure 5).

Task

Observers had to judge the position of the probe with respect to the path of the moving target in a 2 AFC task.
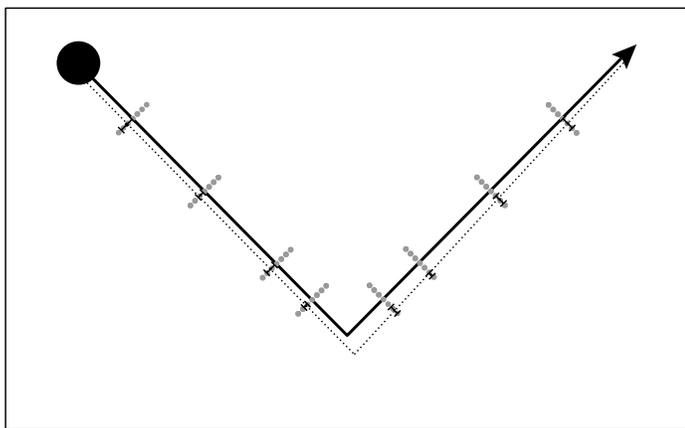

Figure 5. Reconstructing the target trajectory from an internal representation. Small gray circles represent positions of the comparison probe flashed after target disappearance. The solid line represents the target's actual path, and the dashed line represents the linear regression (before and after the turn) interpolated from the group mean reported (probed) positions (solid dark circles).

For each combination of target position (8) and probe location (7), a given observer ran 20 trials, for a total of 560 (=20 × 8 × 7) trials.

Analysis

The reported path of the target at each of the eight tested locations (distinct experimental blocks) was analyzed separately. Within each block, responses were fitted with a psychometric curve to determine the PSE signifying a remembered point along the target trajectory. The coordinates of the four estimated points along the pre-turn target trajectory were then fitted with a linear regression; similarly, the four points along the post-turn trajectory were also fitted with a separate linear regression. A composite tracing of the remembered path of the moving object was constructed from the two linear regressions with the intersection of the two regressions calculated as the remembered path's turn-point.

Results

The averaged best fit tracing of the remembered path of the moving target is shown in Figure 5. The calculated position of the turn point was displaced, but not backwards along the post-turn trajectory as we observed in Experiment 1. In the horizontal direction, the average perceived turn-point of the target was 13.4 ± 4.5 arcmin to the right of (beyond) the actual turn-point ($t(3) = 2.99$, $p = 0.058$). In the vertical direction, the average perceived turn-point of the target was 37.3 ± 9.0 arcmin below the actual turn-point ($t(3) = 4.12$, $p = 0.026$).

Discussion

Here the reconstruction of the trajectory includes an interpolated turn-point that is neither veridical, nor shifted backwards from the eventual trajectory as we found in prior experiments. It is instead shifted horizontally forward, and vertically downward. The calculated angle of the turn in the reconstructed trajectory is precisely orthogonal, suggesting that the gestalt perception of the trajectory's overall shape is both extremely accurate and likely unified. Indeed, if the object's perceived path were a stitched-together, piecewise representation, we would expect the motion mislocalization effects that shift the turn-point (Frolich, repmo, onset repulsion) to skew the perceived angle of the turn. We are faced with an inconsistency between the instantaneously perceived position of the turn-point (single frame snap-shot) and the post-hoc position of the turn-point extrapolated from the stored internal representation of the target's entire trajectory. In other words, once the stimulus is turned off, and an internal,

post-sensory representation of target position develops, the representation is actively distorted by forces as yet unknown (but see Experiments 5–8) in a particular direction, but the direction of the distortion does not remain fixed over the time spent in post-sensory stores.

It is important to note that the shifts of the turn-point along the vertical and horizontal dimensions were affected differently as compared to Experiment 1: the horizontal coordinate, which was shifted before the actual turn was now shifted beyond, while the vertical coordinate continued to be shifted in the same direction as before. This is consistent with a proposal that the forces distorting turn-point position along the two motion axes are likely to be different, a proposal that we will be exploring in subsequent experiments.

Experiment 5a: Small target (horizontal shift)

In all experiments thus far, the target subtended nearly a degree of visual angle. Target size could have had some effect on the direction and magnitude of the perceived displacement in turn-point position, as target size is likely to affect positional uncertainty, which provides a substrate for the bias that we report here. To explore this possibility further, we reduced the size of the target to the smallest possible while maintaining target visibility, repeated Experiment 1 and noted how the effect along each of the two dimensions changed.

Participants

Eight observers (including one author) with normal or corrected to normal vision participated.

Stimuli

In comparison with Experiment 1a, the target was considerably smaller (Figure 6a). It was two pixels in diameter and subtended 3.8 arcmin of visual angle.

Task

As before, observers had to judge the horizontal position of the turn-point of the target with respect to the fixation point. There were 140 (=20 trials/position × 7 positions) trials per observer.

Results

Overall, the perceived position of the turn-point was 9.6 ± 2.5 arcmin to the left of the actual turn-point

(Figures 6b and 6c). The direction of the shift was remarkably consistent, as 7/8 observers perceived a leftward shift in turn-point position (Figure 6b). The shift in perceived position was significant ($t(7) = 3.40$; $p = 0.008$), and was similar in direction to the shift reported in Experiment 1a, albeit of somewhat smaller magnitude.

Discussion

Reducing the size of the target by nearly 95%, from 0.87 deg. to 0.06 deg., as compared to Experiment 1a diminished the magnitude of the perceived horizontal displacement in turn-point location (45% decrease, from 17.3 arcmin to 9.6 arcmin on average), but did not eliminate it entirely. Looked at another way, the magnitude of the perceived shift relative to the diameter of the target in the present experiment, was larger than that in Experiment 1a. The shift in Experiment 1a was about two-thirds the radius of the target but five times that in the present experiment. Regardless of what the correct perspective is on how to compare the two effects, it is indisputably clear that the force(s) that caused the horizontal bias in the original Experiment 1a with a large target remains just as strong in biasing our perception of the horizontal position of the fifteen-fold smaller target used here.

Experiment 5b: Small target (vertical shift)

Experiment 5a was repeated but observers' perceptions of the vertical coordinate of the turn-point were examined.

Participants

Eight observers (including one author) with normal or corrected to normal vision participated.

Stimuli

The target was the same size as in Experiment 5a.

Task

Observers judged the vertical position of the turn-point of the target with respect to nearby hash marks, exactly as in Experiment 1a. All task parameters were identical to the vertical coordinate task of Experiment 1a (Figure 7a). As before, there were 140 (=20 trials/position × 7 positions) trials per observer.

a)
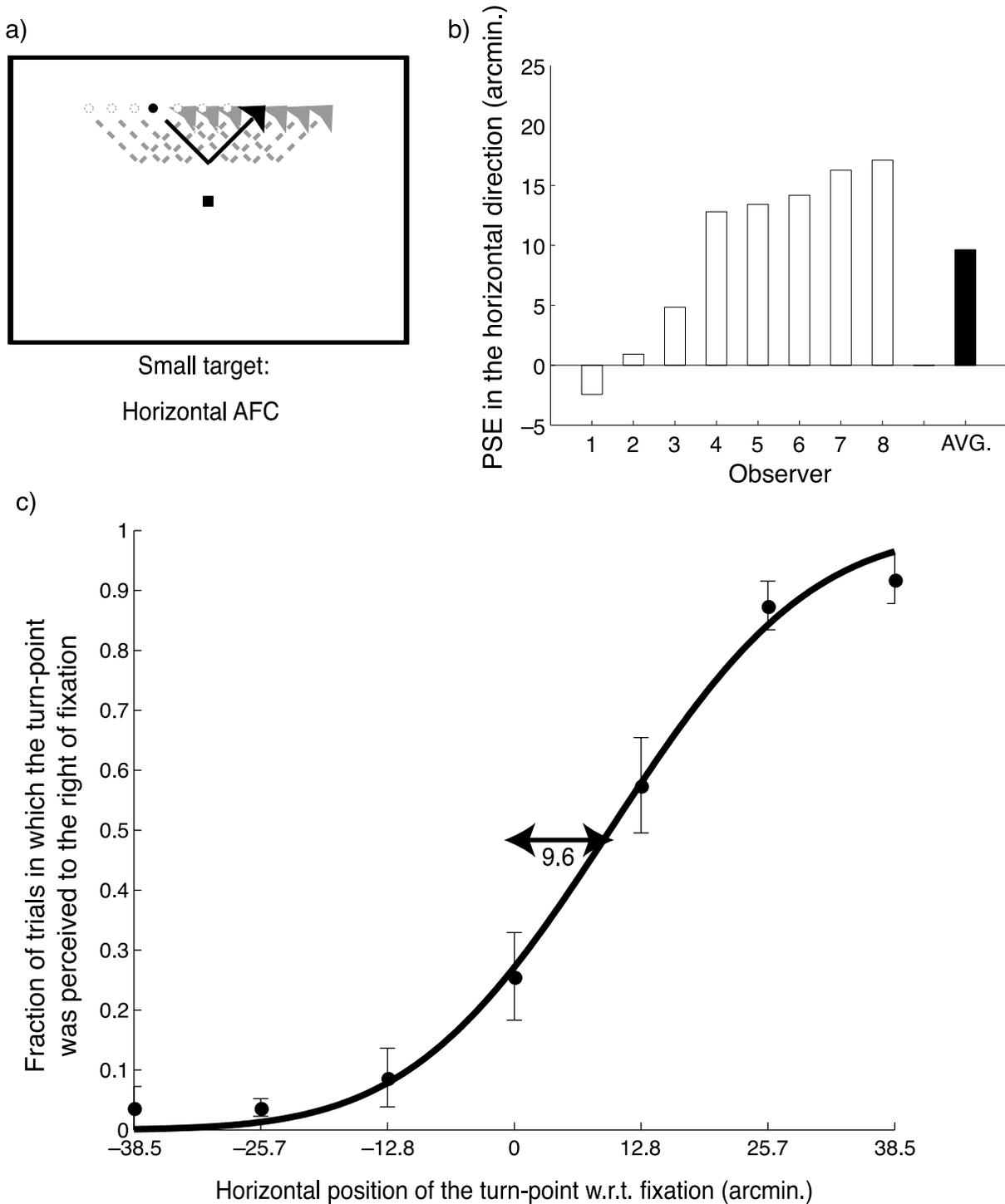

Small target:

Horizontal AFC

b)

c)

Figure 6. A tiny target—judgments of horizontal turn-point position. a) Schematic of the experimental display. b) Effect magnitude (PSE) for each individual observer and group mean (black bar). c) Pooled observer data and the least-squares psychometric curve fit. Error bars are one *SEM*.

Results

Overall, the perceived position of the turn-point was 3.7 ± 3.2 arcmin above the actual turn-point (Figures 7b and 7c), but the shift was not significant ($t(7) = 1.06$; $p = 0.32$).

Discussion

In effect, there was no consistent shift in displacement in the vertical dimension when the target's size was substantially reduced. This result is at odds with that of Experiment 1a with the larger target, in which the
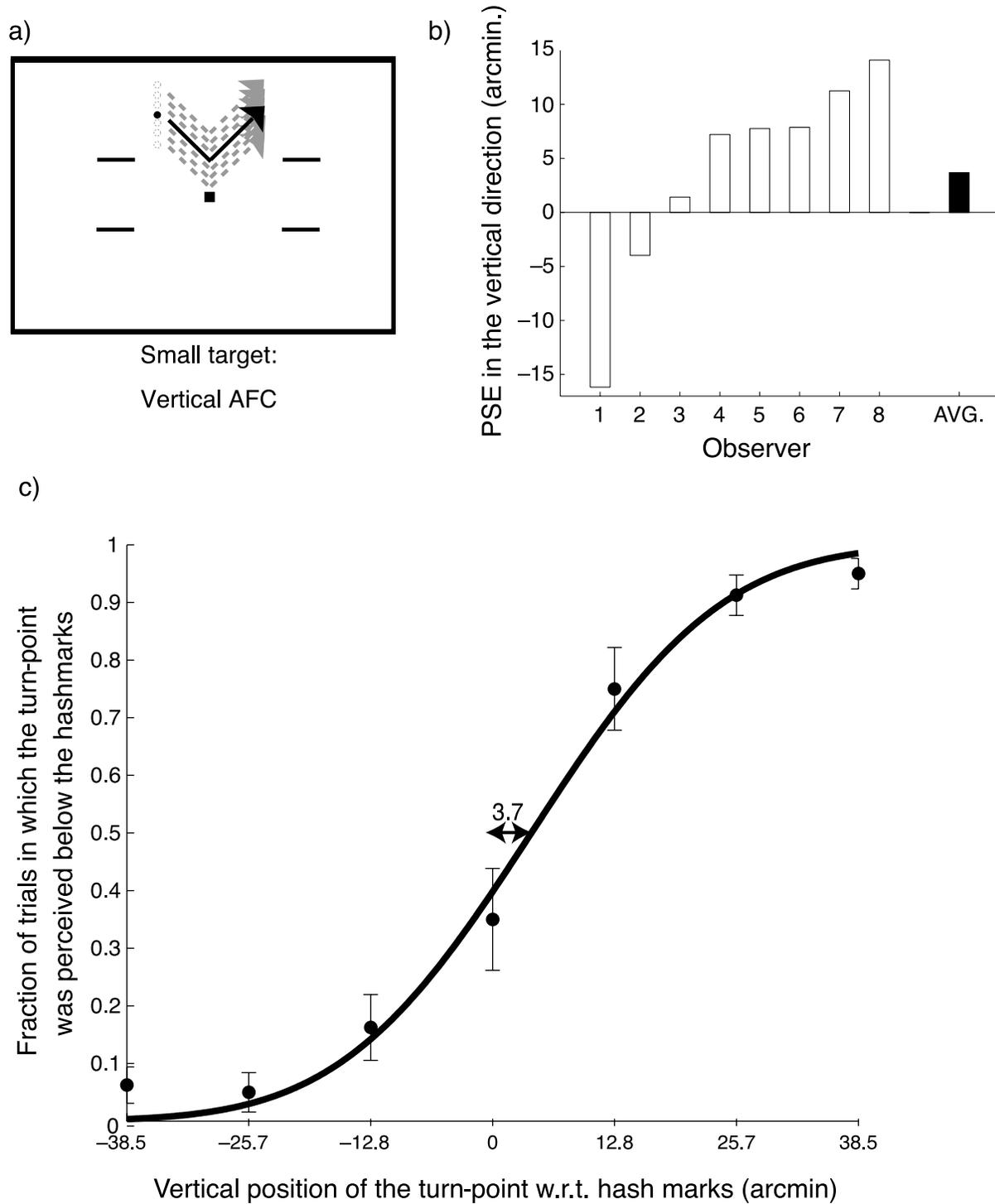
a)

Small target:

Vertical AFC

b)

c)

Figure 7. A tiny target—judgments of vertical turn-point position. a) Schematic of the experimental display. b) Effect magnitude (PSE) for each individual observer and group mean (black bar). c) Pooled observer data and the least-squares psychometric curve fit. Error bars are one *SEM*.

perceived position of the turn-point was biased signifi-cantly below its true position, and with that of Experi-ment 5a with a target of identical size as here, in which the perceived horizontal coordinate of the turn-point did exhibit a (leftward) bias. The only difference in stimulus or task parameters between Experiments 1a and 5b is the

size of the target, and therefore that must be at the core of the discrepancy in the vertical bias. There is likely to be less uncertainty about the location of the center of a miniscule target than a larger one, and the enhanced precision could account for the disappearance of the bias here. Obviously, this explanation is not a complete one, as

it ignores the fact that although the vertical bias disappears, a strong horizontal bias still remains. From this, one can infer that the perceptual forces that drive the horizontal and vertical biases in the large target condition must be distinct, and that only one of these forces is affected by target size.

Experiment 6: The turn-point shift cannot be derived from known perceptual effects

To further explore the underlying perceptual cause of the effect, one must ask if the turn-point shift can be derived from known perceptual effects of positional error involving single, unidirectional trajectories. Our stimulus can be thought of as consisting of two trajectories along two distinct directions. If the turn-point is represented as the termination of the initial, pre-turn trajectory, we expect a contribution of representational momentum (repmo), an effect in which the representation of the terminal point's position is carried forward along its path (Freyd & Finke, 1984). In our case (in Experiment 1a), for a target that moves down and right and then turns 90 degrees and heads up and to the right, representational momentum would push the perception of the end of the first part of the trajectory down and to the right (Figure 8a). If the turn-point is represented as the origin of the second, post-turn trajectory, we might expect contributions from either of two onset effects that are in opposite directions: the Fröhlich effect, which involves the mislocalization of a fast moving target's origin forward in the direction of motion (Fröhlich, 1923; Musseler & Aschersleben, 1998), and the onset repulsion effect (ORE), which involves the mislocalization of a moving target's origin backwards along its path of motion (Thornton, 2002). In our case, the Fröhlich effect would push the perceived position of the turn-point up and to the right (Figure 8a); ORE would push our perceived turn-point down and to the left [A Fröhlich effect is typically exhibited if the onset location is predictable (Musseler & Kerzel, 2004), which is largely the case in our experiments, or if the boundary of a larger enclosing window is near the onset location (Hubbard & Motes, 2005), which is not the case in our experiments]. Thus, on the basis of all the mislocalization effects (onset repulsion, representational momentum, and the Fröhlich effect) that have a single target moving with uniform velocity as the stimulus, one would predict a different direction of bias in positional estimates of the turn-point. However, as Figure 8a illustrates, representational momentum or the Fröhlich effect cannot alone or in combination explain the turn-point shift.

On the other hand, the mechanisms underlying the onset repulsion effect have the potential to explain the turn-point shift. For an object moving up and to the right, the observer's estimate should be biased below and to the left of the actual onset (Figure 8a), the same direction as the turn-point shift. It should be pointed out that the stimulus and procedural parameters that give rise to onset repulsion are different from the ones used to obtain the turn point shift-onset repulsion is observed at slower target speeds, with a pointing task, and at unpredictable target locations (Thornton, 2002). Thus a simple test to establish if onset repulsion would be sufficient to explain the turn-point shift was to test if onset repulsion occurred if the same parameters from Experiment 1a were used but the pre-turn portion of the trajectory was ablated.

Participants

Six naive, unpaid observers with normal or corrected to normal vision participated.

Stimuli

In brief, the target appeared near the midline and moved through only the second part of the trajectory from Experiment 1a on each trial. In more detail, a circular target 0.87 deg in diameter appeared 3.4 deg above the fixation point either directly aligned or 0.3, 0.6, or 0.9 deg to the right or left and moved diagonally up and to the right at a 45 deg angle at one of five speeds (4.1, 8.2, 12.3, 16.4, and 20.5 deg/sec). A central fixation point 0.10×0.10 deg was constantly visible. The fixation point and all targets were presented in white (83.5 cd/m^2) against a black background (0.215 cd/m^2). For comparison, the full trajectory from Experiment 1a was tested at the same five speeds in a separate experimental block.

Task

On the no-turn trajectory block of trials, observers had to judge the horizontal position of the appearance point of the target with respect to the fixation point. The stimulus display and task were similar to those used to examine onset-repulsion. For each speed (5) tested, observers ran 140 (=20 trials/position $\times$ 7 positions) trials for a total of 700 trials. On the turn-trajectory block of trials, the task was the same as in Experiment 1a: observers had to judge the horizontal position of the turn-point relative to fixation. Again, there were 700 total trials per observer, equally distributed among the five speeds tested.

Results

Viewing only the second half of the trajectory at the speeds we tested, observers failed to consistently demonstrate a significant onset repulsion effect. Conversely, viewing the complete elbow trajectory at the same speeds,
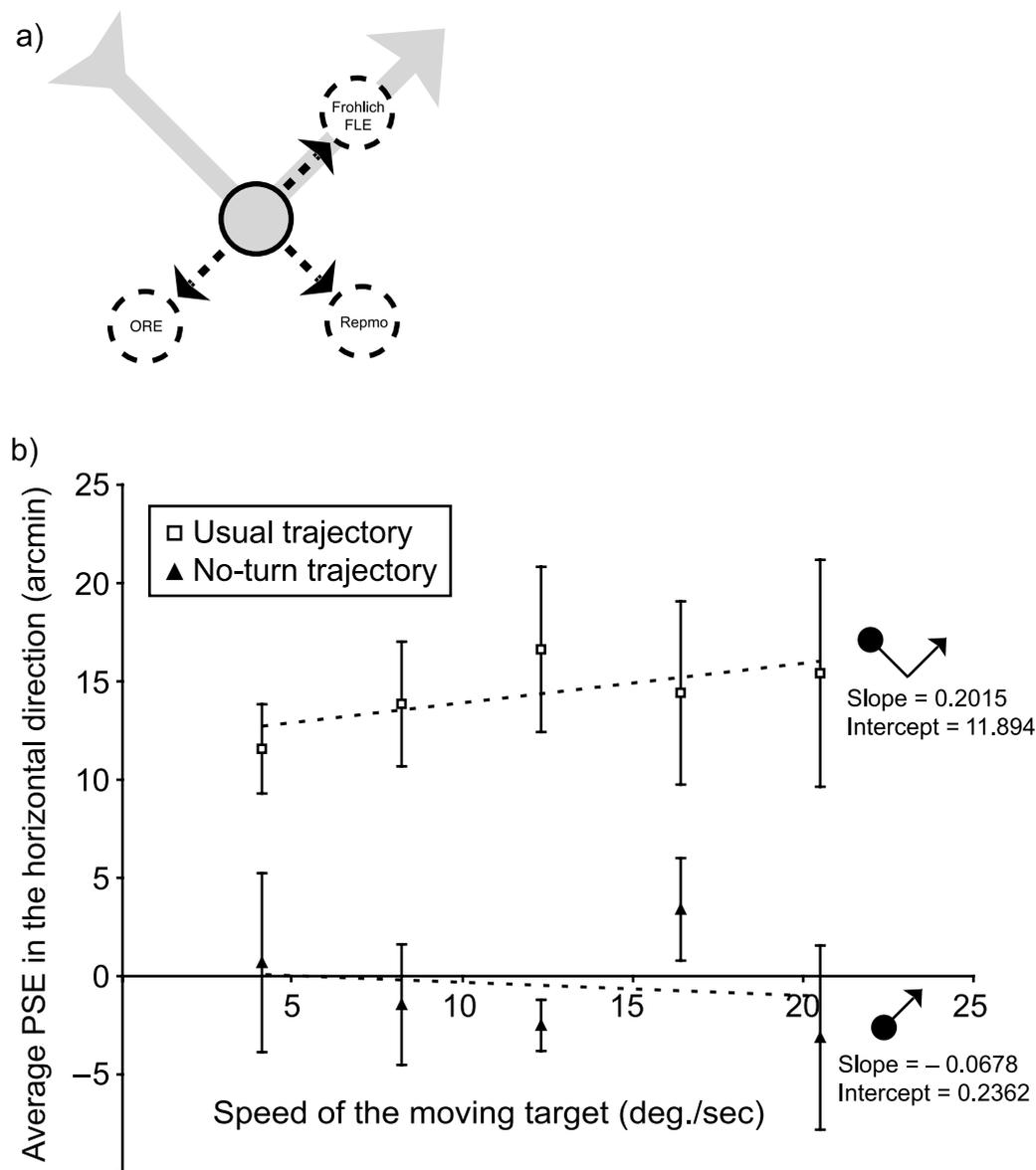
Figure 8. The onset repulsion effect cannot account for the turn-point shift. a) Predicted contributions of known effects on the perception of the turn-point. Representational momentum (repmo) is projected forward from the end of the first leg of the trajectory. The Frohlich effect is projected forward along the direction of motion from the start of the second leg of the trajectory, and the onset repulsion effect (ORE) is projected backwards along the direction of motion from the start of the second leg of the trajectory. A differential latency account of flash-lag predicts that the target will be perceived further along its trajectory at the moment of the transient event. b) Average shift in the horizontal direction (point of subject equality) of the turn-point location as a function of target speed for the usual and no-turn trajectories. The usual trajectory condition contains the abrupt orthogonal turn. The no-turn trajectory condition contains only the second half of the usual trajectory. In this case, observers had to judge the position of the onset of the motion. Dashed lines indicate best fit linear regressions. Error bars are one *SEM*.

observers' estimates of the turn-point shifted backward significantly ([Figure 8b](#)).

Discussion

While the direction of the turn-point shift is consistent with that of onset repulsion observed in previous studies (Actis-Grosso & Stucchi, [2003](#); Sheth & Shimojo, [2000](#); Thornton, [2002](#)), the comparable onset trajectory with the comparable speed parameter did not generate an onset repulsion effect at all. This is not surprising since onset repulsion—a displacement in estimates of the position of the onset of motion in the direction opposite to the motion—is typically observed when the onset position is unpredictable (Musseler & Kerzel, [2004](#)); from trial to

trial of our study, the location of the turn-point (and in the present experiment, the location of the onset point of the no-turn trajectory) was highly predictable to within a small fraction of a degree. Secondly, onset repulsion is typically found when the observer has to perform a motor pointing task, not on relative judgment tasks (Kerzel, 2002); in our study, the observer was engaged in a relative judgment task and motor accuracy had little bearing on performance. Thirdly, onset repulsion is observed at slower target speeds (Kerzel, 2002). If onset repulsion were sufficient to explain the turn-point shift, the magnitude of the turn-point shift should decrease with increase in target speed. As Figure 8b shows, the effect did not decrease with increase in target speed; if anything, there was a modest increase. In sum, on an experiment with parameters similar to those used in Experiment 1 and across a range of target speeds, we failed to find an onset repulsion effect. A more careful look at past studies (Actis-Grosso & Stucchi, 2003; Sheth & Shimojo, 2000; Thornton, 2002) confirmed that the onset repulsion effect operates over a different set of parameters from those used here. Thus, the turn-point shift is separate from onset repulsion and distinct mechanisms are likely to underlie it.

Experiment 7: No post-turn trajectory

What then are the forces that give rise to the leftward and downward directions of bias in judgments of turn-point position? In order to address this question, we manipulated aspects of the stimulus display, such as the trajectory of the target's motion, or the location of the fixation point, in order to reduce, eliminate, or even reverse the bias.

First, we probed the cause behind the bias in the horizontal direction. Figure 8a depicts an established effect called representational momentum (Freyd & Finke, 1984), in which estimates of the position of the end-point are biased forward. On this basis, we predict that eliminating the trajectory beyond the turn will dramatically change the direction of the bias of the turn-point from one behind the motion to one beyond.

Participants

Eight observers (including one author) with normal or corrected to normal vision participated.

Stimuli

In comparison with Experiment 1a, the target was extinguished upon reaching the turn-point. That is to say, the target terminated at the turn-point (Figure 9a).

Task

Observers had to judge the horizontal position of the end-point of the target with respect to fixation. There were 140 (=20 trials/position × 7 positions) trials per observer.

Results

The end-point was perceived −5.4 ± 2.2 arcmin to the right of the true end-point (Figures 9b and 9c), namely forward in the direction of the target's motion, and this shift was marginally significant ($t(7) = -2.37$; $p = 0.052$). A majority (7/8) of observers reported a rightward shift in end-point position (Figure 9b).

Discussion

Removing the portion of the target's path following the turn had a dramatic effect, in that the bias in horizontal positional judgments switched direction. The end-point of the target was no longer perceived backward or behind the motion but beyond it. Although the stimulus and task parameters used here differ from those of repmo, the direction of the bias reported here is consistent with repmo.

Of importance to the present purpose, there was no motion following the turn, highlighting the importance of the *post*-turn trajectory in causing the backward bias. In other words, upward and rightward motion of the target following the turn drives positional judgments away from those directions, thus leading to the backward bias in turn-point position estimates.

Representational momentum studies provide a basis for predicting a similar forward bias in the vertical direction, which in our case means a bias down when the upward post-turn trajectory is not present. Therefore, an argument can be made that the same force, namely rightward and upward motion following the turn, is responsible for the leftward and downward bias in our studies. However, Experiments 5a and 5b (and Experiment 4 to a certain extent as well) revealed that different mechanisms underlie bias in the vertical and horizontal directions. Moreover, repmo, at least in our hands, has a small, marginal effect on positional judgments—probably not enough to account for the magnitude of the vertical bias. Therefore, other candidates to account for the downward vertical bias must be considered.

Experiment 8: Fixation point inside the target's motion trajectory

One such promising candidate is the fixation point. Foveal attraction has been found to be a highly effective
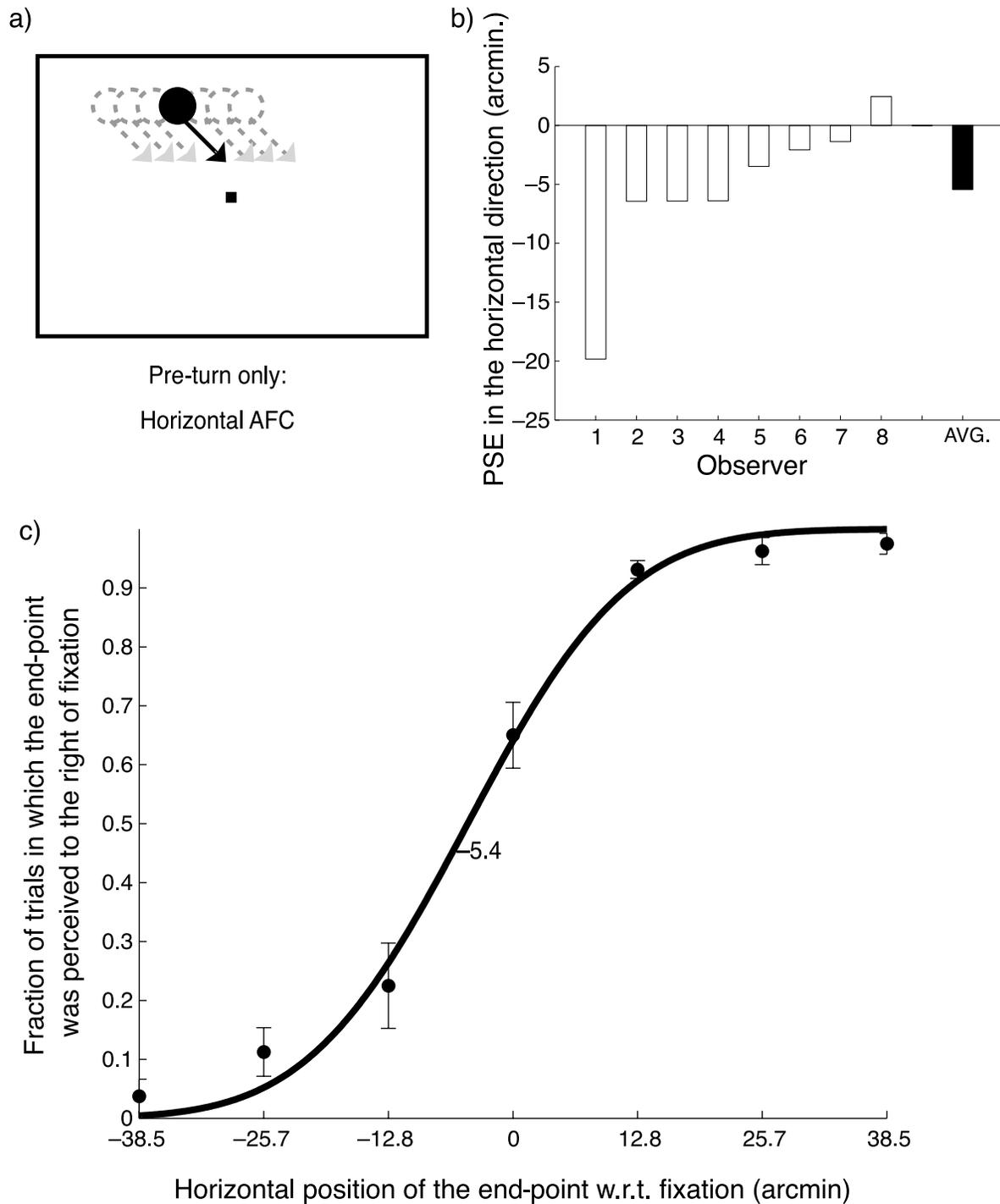
Figure 9. Pre-turn trajectory only. a) Schematic of the experimental display. b) Effect magnitude (PSE) for each individual observer and group mean (black bar). Observers had to judge the horizontal coordinate of the turn-point relative to fixation. c) Pooled observer horizontal bias and the least-squares psychometric curve fit. Error bars are one *SEM*.

mechanism in biasing positional judgments of a stationary target (Helmholtz, 1866; Mateeff & Gourevich, 1983; Sheth & Shimojo, 2001) but whether or not foveal attraction can bias positional judgments of a moving target remains to be seen. In all experiments thus far, the fixation point was outside of the (pre- and post-turn)

trajectory, i.e. below the target (cf. Figure 1), and positional judgments were biased down. If the fixation point were to be located inside the trajectory, i.e. above the turn-point, and judgments of turn-point position were to be biased *up,* then this would clearly implicate foveal attraction as a mechanism underlying the vertical bias.

Participants

Eight observers (including one author) with normal or corrected to normal vision participated.

Stimuli

In contrast to previous experiments, the central fixation point was inside the trajectory in this experiment. That is
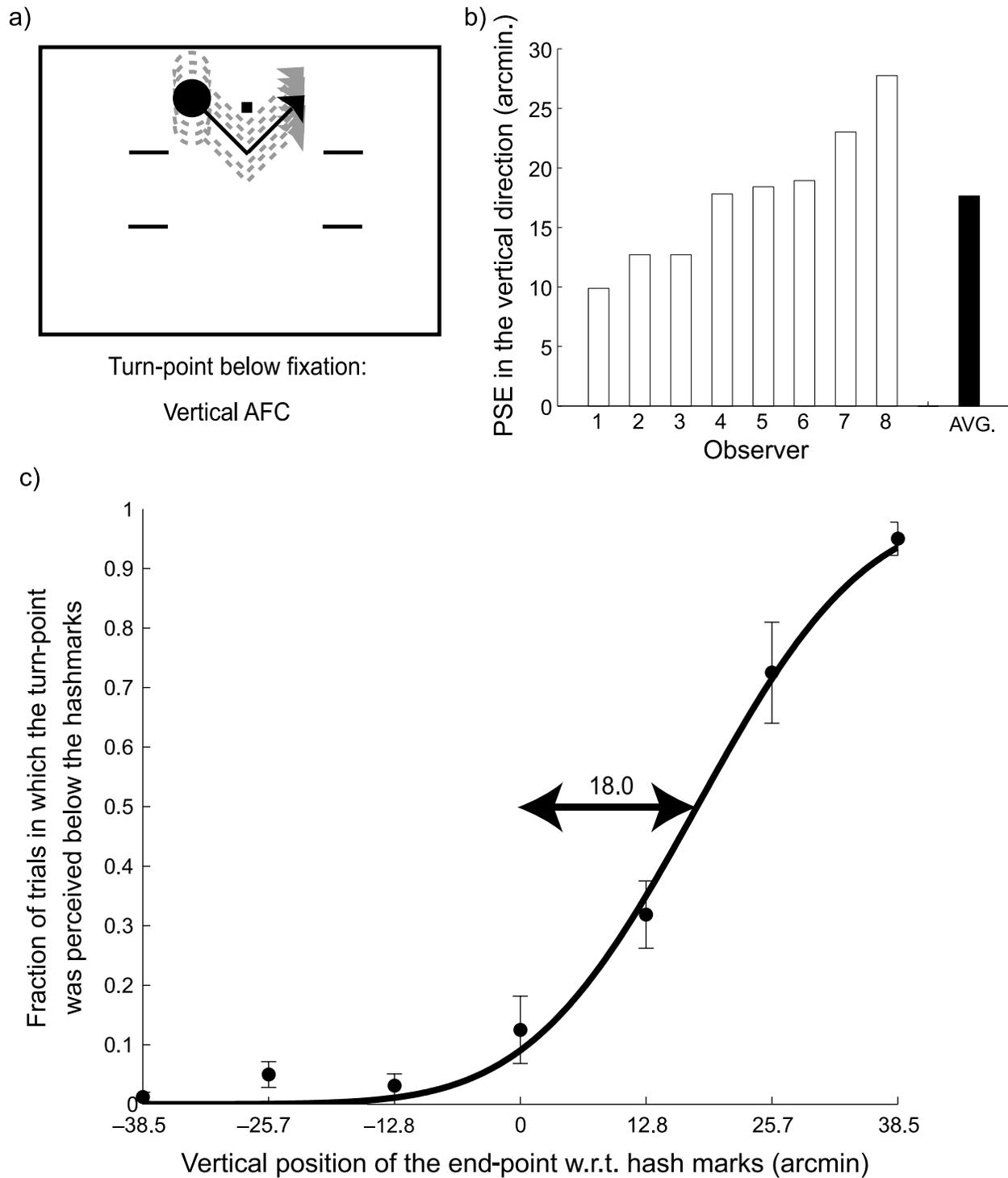

Figure 10. Fixation point above the turn-point. a) Schematic of the experimental display. b) Effect magnitude (PSE) for each individual observer and group mean (black bar). Observers had to judge the vertical coordinate of the turn-point relative to the hash-marks. c) Pooled observer vertical bias and the least-squares psychometric curve fit. Error bars are one *SEM*.

to say, the fixation point was located 3.4 deg above the turn-point in the display (Figure 10a). All other stimulus parameters, including fixation point size, target speed, and so on remained the same as in Experiment 1a.

Task

Observers had to judge the vertical position of the turn-point of the target with respect to the hash marks. There were 140 (=20 trials/position × 7 positions) trials per observer.

Results

The perceived vertical position of the end-point was 17.7 ± 1.9 arcmin above the true location (Figures 10b and 10c), and was highly significant ($t(7) = 8.49$; $p < 0.0001$). The results were remarkably consistent across our sample: Estimates of all eight observers were biased upward (Figure 10b).

Discussion

Here, the fixation point was located above the turn-point, and observers reported perceiving the turn-point above its true position. In contrast, the fixation point was located below the turn-point in Experiment 1a, and observers reported perceiving the turn-point below its true position. Thus, foveal attraction appears to be a likely candidate for the vertical bias. Moreover, given that the trajectory remained unchanged from before while the vertical bias switched direction, post-turn trajectory cannot be causing the vertical bias.

As mentioned earlier, from studies of motion-related mislocalization, such as the flash-lag (Nijhawan, 1994) and the flash-drag (Whitney & Cavanagh, 2000) effects, one would expect the turn-point to be displaced in the direction of consistent motion, not against it, but with this kind of motion we found a displacement against the motion in both the horizontal and the vertical directions. Thus, the twin forces of post-turn trajectory and foveal attraction were strong enough to offset the motion induced mislocalizations.

General discussion

Here we demonstrate and explore a new example of motion-related perceptual mislocalization: The "turn-point shift" refers to the tendency of observers to perceive the point of a moving target's orthogonal direction change backwards along its eventual trajectory. We show the consistent presence of this effect whether or not there is an abrupt change of direction (Experiments 1a–1c). While attention may modulate the turn-point shift, it is likely not the principal mechanism responsible for the turn-point shift (Experiment 2). The turn-point shift is not a sensorimotor effect, as evidenced by the finding that the observer's eye position just before or just after the turn had little relationship with the direction of the reported bias (Experiment 3). This suggests that the turn-point shift is an effect involving perceptual decision, similar to but distinct from other known effects of localization such as onset repulsion, Fröhlich effect, and representational momentum (Experiment 6). Additional experiments probed the nature of the unique mechanisms or forces underlying the turn-point shift. Experiment 4 showed that when the observer had to *post-hoc* localize the entire trajectory, the reconstructed turn-point was no longer biased backward but rather forward in the direction of motion. Experiment 5 further found that the forces responsible for the turn-point shift along the two cardinal axes are distinct, because when the target size was reduced, the bias in the vertical direction disappeared while the bias along the horizontal direction remained intact. This was confirmed in later experiments: Motion following the turn indirectly repulsed, and thereby biased, estimates of the horizontal coordinate of the turn-point away from the post-turn motion (Experiment 7), and the presence of a fixation spot attracted estimates of the vertical coordinate of the turn-point toward it (Experiment 8). In the following sections, we analyze and interpret our results. In particular, we argue for the uniqueness of the stimulus and the turn-point shift in the context of known effects, discuss the mechanisms underlying the shift, and speculate about some implications.

The turn-point shift and mislocalization. The turn-point shift is distinct from previously studied effects of position localization both in the nature of stimulus displayed and in the direction of mislocalization observed. Motion-based effects of mislocalization typically fall into two classes. Effects such as Fröhlich, representational momentum, and onset repulsion comprise the first class. Here, the stimulus moves along one particular direction and the observer has to localize the trajectory's start or end. In the present configuration, the stimulus abruptly changes direction midway through the motion and the observer has to localize the transient change. This is a key difference: mislocalizing the start- or end-points of a trajectory has little bearing on perceived continuity of the rest of the trajectory; in contrast, mislocalizing a point midway in the trajectory has the potential to perturb the perceptual continuity of the ongoing motion and perceptually mis-align the pre- and post-legs of the trajectory relative to one another, thereby creating a need to reconcile motion along the different vectors. The second class consists of effects like flash-lag and flash-drag. Here, a transient marker, i.e. a flash, is distant from a moving stimulus. In the present configuration, the transient marker, i.e. the turn, is

embedded within the trajectory itself. This is a key difference: Perceptual shift of a marker has little bearing on the perception of motion that is remote from it, whereas a similar shift of a point in the middle of a trajectory might disrupt perceived motion continuity.

From the above discussion, one can safely conclude that the turn-point shift is not some variant of a known mislocalization effect or effects. This is consistent with our finding that the turn-point shift cannot be accounted for by the first class of effects described above or, for that matter, by the second, e.g. the host of accounts of the flash-lag effect all explain why the turn-point in our stimulus should be shifted forward along the eventual post-turn trajectory (Eagleman & Sejnowski, 2000; Kanai, Sheth, & Shimojo, 2004; Nijhawan, 1994; Patel et al., 2000; Sheth, Nijhawan, & Shimojo, 2000), whereas the turn-point is misperceived behind the eventual trajectory.

Thus, the turn-point shift is a class unto itself, and an opportunity to study a possible inconsistency between point and trajectory—aspects of the object that are processed differently by the visual system—and to understand how our perceptual decision system resolves it. In this regard, we found that when the observer is called upon to localize the turn-point as soon as the target stimulus makes the turn, its perceived horizontal position is represented behind the actual turn, but when called upon to localize after the post-turn trajectory is extinguished the post-sensory horizontal position is represented ahead of the actual turn. Thus, there are at least two representations of the turn-point that are mutually inconsistent. From our findings, it appears that the two are independently accessible by the perceptual decision system (i.e., by the observers) for conscious report, and that what we get consciously is always a unique representation with all kinds of processed information bound together. The two mutually inconsistent representations do not have to co-exist, as the post-sensory trajectory based representation of the turn-point (Experiment 6) is summoned later in time than the direct judgments of turn-point position, as in most of our experiments (1–5, 7–8). This implies that with a new task at hand, a new internal representation emerges; the perceptual decision system does not check for consistency between the new representation and the old one, perhaps because it does not need to.

From a number of visual experiments, we have repeatedly learned that local and global percepts can be mutually inconsistent (e.g., local brightness and surface lightness). We understand that the visual system is doing a good but imperfect job at hiding mutual inconsistency in internal representations, but the question remains as to how we achieve this. Our study of mislocalization in the presence of stimulus motion suggests that new task demands generate new representations; these representations are constrained and confined to the task at hand and this combined with a failure to cross-check different "in-the-moment" representations formed at different times is a

recipe for multiple, mutually inconsistent task-dependent representations of a stimulus.

Mechanisms underlying the turn-point shift. One of the hallmarks of the turn-point shift is that the bias is not in the direction of motion but against it. This is different from motion-based mislocalization effects, e.g. representational momentum, Frohlich, flash-lag, flash-drag and so on in which the bias is in the same direction as the motion. Therefore, the key question is what forces are pulling the percept of the turn-point back. There are two plausible mechanisms: foveal attraction and landmark attraction/repulsion. Experiments suggest that the fixation spot vertically pulls the perceived turn-point towards it: When the fixation point is above the turn, the turn-point is misperceived up; when fixation is below the turn, the turn-point is misperceived down. This is interesting because it shows a novel interaction between foveal attraction and motion: in pulling the turn-point towards it in the vertical direction, fixation is strong enough to overpower the drag of motion. In contrast, fixation is not such a dominant force on the other motion-based mislocalization effects listed above.

This begs the question: under what conditions does foveal attraction prevail over the drag from motion? Although we do not know for certain, we again point to a critical difference in the stimulus display from those used in the past that may be a cause. In all other effects, the motion is continuous and uniform. Here, the stimulus changes direction abruptly midway through: the turn-point is a break in the motion. A reasonable idea is that this difference in stimulus underscores the surprisingly powerful effect of foveal attraction in the turn-point shift. The discontinuity is separable perceptually from the motion gestalt and can be processed as an isolated, stationary point in space for which the fovea has been shown to exert a powerful pull (Mateeff & Gourevich, 1983; Sheth & Shimojo, 2001). This interpretation implies that a discontinuity in the motion can be processed apart from the rest of the trajectory even while it is integrated into the motion gestalt. In more general terms, it argues against the idea that a stimulus or event can give rise to just one percept. (As an aside, Experiment 5b suggests that foveal attraction varies with target size. This bears some analogy with Newton's law in physics, namely that gravitational pull varies with target mass. Clearly, more experiments are required to test the limits of this proposed analogy.)

In sum, fixation pulls vertically the perceived turn-point toward it but what affects the horizontal coordinate? Experiments suggest the post-turn trajectory repulses the perceived horizontal coordinate of the turn-point away from it: When the post-turn trajectory of the target is up and to the right, the turn-point is misperceived left; when no post-turn trajectory is present, the turn-point, or end-point of the rightward motion, is misperceived right. The turn-point's position is typically estimated just after the target makes the turn. During this time, the target is moving along its post-turn trajectory. Estimates of the exact location of the turn-point would be uncertain but a

reasonable calculation is that the turn-point must not overlap with points along an ongoing post-turn trajectory that is being perceived simultaneously as the turn-point position is being judged. This can explain why estimates of the turn-point are biased away from the direction of the post-turn trajectory. A partial validation of the idea is found in the results of the trajectory probe experiment. Here, one has to estimate target position following both the turn *and* the post-turn motion. At the time of the decision, the target is long gone; therefore, a repulsive probabilistic bias away from the post-turn trajectory is unlikely. This is the case: as Figure 5 shows, the reconstructed turn-point is now biased right, in the direction of the post-turn motion. Thus, positions occupied by the moving stimulus following the turn appear to bias estimates of turn-point position. The results of Experiment 5a showing that a horizontal bias remained even when the target's size was reduced are understandable in the context of this idea as well. The target, regardless of its size, will always pass through points in space after the turn, which will continue to bias the probability distribution of turn-point estimates away from the more recent post-turn path—smaller the target, smaller the space occupied by the post-turn points, and smaller the absolute size of bias.

We pose a similar question as before. Why is it the case that on the turn-point shift, unlike on a host of motion-based mislocalization effects, stimulus motion is not able to drag turn-point position with it? Once again, we do not definitively know the answer but make note that the turn-point is a salient point in the middle of the motion, a display unique among motion-based mislocalization effects, and contend that its uniqueness allows it to be dislodged in the mind and be processed separately from the rest of the motion trajectory.

We conclude with a number of issues that remain unresolved from our study. What is the nature of the interaction between the two forces proposed here? Is the turn-point a unique kind of discontinuity or are there others (such as a transient change in target color, gap in the motion, and so on)? Finally, a point about potential implications for perception and decision: Are conflicts left unresolved because the perceptual decision system compartmentalizes mutually inconsistent perceptual decisions that arise from different task demands, or is it the case that percepts formed at different times are compartmentalized and never cross-validated with one another? Our results are consistent with both possibilities that we raise here, and point toward a mechanism or mechanisms by which our perceptual decision systems are stitching together the illusion of a consistent unique world.

Acknowledgments

Corresponding authors: Dylan Nieman; Bhavin R. Sheth.
Emails: dylan_nieman@urmc.rochester.edu; brsheth@uh.edu.
Address: Department of Surgery, University of Rochester, 601 Elmwood Avenue, BOX SURG, Rochester, NY 14642, USA; University of Houston, Houston, TX 77204-4005, USA.

References

Actis-Grosso, R., & Stucchi, N. (2003). Shifting the start: Backward mislocation of the initial position of a motion. *Journal of Experimental Psychology: Human Perception and Performance, 29,* 675–691. [PubMed]

Brainard, D. H. (1997). The Psychophysics Toolbox. *Spatial Vision, 10,* 433–436. [PubMed]

Cornelissen, F. W., Peters, E. M., & Palmer, J. (2002). The eyelink toolbox: Eye tracking with MATLAB and the Psychophysics Toolbox. *Behavioral Research Methods in Instrumental Computer, 34,* 613–617. [PubMed]

Eagleman, D. M., & Sejnowski, T. J. (2000). Motion integration and postdiction in visual awareness. *Science, 287,* 2036–2038. [PubMed]

Freyd, J. J., & Finke, R. A. (1984). Representational momentum. *Journal of Experimental Psychology: Learning, Memory, and Cognition, 10,* 126–132.

Fröhlich, F. W. (1923). Über die Messung der Empfindungszeit (Measuring the time of sensation). *Zeitschrift für Sinnesphysiologie, 54,* 58–78.

Helmholtz, H. V. (1866). *Handbuch der physiologischen optik.* Leipzig: Voss.

Hubbard, T. L., & Motes, M. A. (2005). An effect of context on whether memory for initial position exhibits a Frohlich effect or an onset repulsion effect. *logy A, 58,* 961–979. [PubMed]

Kanai, R., Sheth, B. R., & Shimojo, S. (2004). Stopping the motion and sleuthing the flash-lag effect: Spatial uncertainty is the key to perceptual mislocalization. *Vision Research, 44,* 2605–2619. [PubMed]

Kanai, R., Sheth, B. R., & Shimojo, S. (2007). Dynamical evolution of motion perception. *Vision Research, 47,* 937–945. [PubMed]

Kerzel, D. (2002). Different localization of motion onset with pointing and relative judgements. *Experimental Brain Research, 145,* 340–350. [PubMed]

Koffka, K. (1935). *Principles of Gestalt psychology* (1st ed.). New York: Harcourt Brace.

Mateeff, S., & Gourevich, A. (1983). Peripheral vision and perceived visual direction. *Biological Cybernetics, 49,* 111–118.

Moore, C. M., & Enns, J. T. (2004). Object updating and the flash-lag effect. *Psychology Science, 15,* 866–871. [PubMed]

Musseler, J., & Aschersleben, G. (1998). Localizing the first position of a moving stimulus: The Frohlich effect and an attention-shifting explanation. *Perception & Psychophysics, 60,* 683–695. [PubMed]

Musseler, J., & Kerzel, D. (2004). The trial context determines adjusted localization of stimuli: Reconciling the Frohlich and onset repulsion effects. *Vision Research, 44,* 2201–2206. [PubMed]

Nieman, D. R., Sheth, B. R., & Shimojo, S. (2005). Mutually incompatible percepts of motion and position of a single visual stimulus. Paper presented at the Annual Meeting of the Society for Neuroscience, Washington, DC.

Nieman, D. R., Sheth, B. R., & Shimojo, S. (2006). Mutually contradictory percepts in motion processing [Abstract]. *Journal of Vision, 6*(6):554, 554a, http://www.journalofvision.org/content/6/6/554, doi:10.1167/6.6.554.

Nijhawan, R. (1994). Motion extrapolation in catching. *Nature, 370,* 256–257. [PubMed]

Ogmen, H., Patel, S. S., Bedell, H. E., & Camuz, K. (2004). Differential latencies and the dynamics of the position computation process for moving targets, assessed with the flash-lag effect. *Vision Research, 44,* 2109–2128. [PubMed]

Palmer, S. E. (1999). *Vision science: Photons to phenomenology*. Cambridge, MA: MIT Press.

Patel, S. S., Ogmen, H., Bedell, H. E., & Sampath, V. (2000). Flash-lag effect: Differential latency, not postdiction. *Science, 290,* 1051. [PubMed]

Pelli, D. G. (1997). The VideoToolbox software for visual psychophysics: Transforming numbers into movies. *Spatial Vision, 10,* 437–442. [PubMed]

Satterthwaite, F. E. (1946). An approximate distribution of estimates of variance components. *Biometrics Bulletin, 2,* 110–114. [PubMed]

Sheth, B. R., Nijhawan, R., & Shimojo, S. (2000). Changing objects lead briefly flashed ones. *Nature Neuroscience, 3,* 489–495. [PubMed]

Sheth, B. R., & Shimojo, S. (2000). In space, the past can be recast but not the present. *Perception, 29,* 1279–1290. [PubMed]

Sheth, B. R., & Shimojo, S. (2001). Compression of space in visual memory. *Vision Research, 41,* 329–341. [PubMed]

Sheth, B. R., & Shimojo, S. (2004). Sound-aided recovery from and persistence against visual filling-in. *Vision Research, 44,* 1907–1917. [PubMed]

Thornton, I. M. (2002). The onset repulsion effect. *Spatial Vision, 15,* 219–243. [PubMed]

Titchener, E. B. (1898). *A primer of psychology*. New York: The Macmillan Company, 1909.

Whitney, D., & Cavanagh, P. (2000). Motion distorts visual space: Shifting the perceived position of remote stationary objects. *Nature Neuroscience, 3,* 954–959. [PubMed]

Whitney, D., Wurnitsch, N., Hontiveros, B., & Louie, E. (2008). Perceptual mislocalization of bouncing balls by professional tennis referees. *Current Biology, 18,* R947–R949. [PubMed] [Article]

Wundt, W. M. (1884). *Traitâe âelâementaire de physique mâedicale* (2. âed. franðcaise, ed.). Paris: J. B. Bailliáere et fils.