
ELSEVIER
VISION
RESEARCH
An International Journal for Functional Aspects of Vision
Experiment 1 ("P" Target)
Biochemistry & Cell Biology • Molecular Biology & Genetics
Anatomy, Physiology, Pathology & Pharmacology • Optics, Accommodation & Refractive Error
Circuitry & Pathways • Psychophysics • Perception • Attention & Cognition
Computational Vision • Eye Movements & Visuomotor Control
ISSN 0042-6989
Volume 51
Issue 16
15 August 2011

Vision Research 51 (2011) 1880–1887

Contents lists available at ScienceDirect

Vision Research

journal homepage: www.elsevier.com/locate/visres

Global flow impacts time-to-passage judgments based on local motion cues

Scott A. Beardsley [a,b,*], Elif M. Sikoglu [b], Heiko Hecht [b,c], Lucia M. Vaina [b,d]

[a] Department of Biomedical Engineering, Marquette University, P.O. Box 1881, Milwaukee, WI 53201, USA
[b] Brain and Vision Research Laboratory, Department of Biomedical Engineering, Boston University, 44 Cummington Street, Boston, MA 02215, USA
[c] Department of General Experimental Psychology, Psychologisches Institut, Johannes Gutenberg-Universität Mainz, Building Taubertsberg II, Wallstrasse 3, 55099 Mainz, Germany
[d] Department of Neurology, Harvard Medical School, 75 Francis Street, Boston, MA 02215, USA

ARTICLE INFO

Article history:
Received 13 December 2010
Received in revised form 28 June 2011
Available online 8 July 2011

Keywords:
Time-to-passage (TTP)
Self-motion
Tau
Time-to-contact (TTC)
Optic flow
Motion perception

ABSTRACT

We assessed the effect of the coherence of optic flow on time-to-passage judgments in order to investigate the strategies that observers use when local expansion information is reduced or lacking. In the standard display, we presented a cloud of dots whose image expanded consistent with constant observer motion. The dots themselves, however, did not expand and were thus devoid of object expansion cues. Only the separations between the dots expanded. Subjects had to judge which of two colored target dots, presented at different simulated depths and lateral displacements would pass them first. Image velocities of the target dots were chosen so as to correlate with time-to-passage only some of the time. When optic flow was mainly incoherent, subjects' responses were biased and relied on image velocities rather than on global flow analysis. However, the bias induced by misleading image velocity cues diminished as a function of the coherence of the optic flow. We discuss the results in the context of a global tau mechanism and settle a debate whether local expansion cues or optic flow analysis are the basis for time-to-passage estimation.

1. Introduction

In daily life, observers routinely make judgments about the arrival of objects moving towards them. By virtue of the available sensory information, such decisions are largely based on visual motion cues on the observer's retinae. Among these cues, one of the most commonly studied is tau, characterized by the ratio between an object's instantaneous angular size and the rate of change of this angular size (Hecht & Savelsbergh, 2004; Lee, 1976; Regan & Gray, 2000; Tresilian, 1991).

$$tau = \frac{\theta}{d\theta/dt} \tag{1}$$

where θ could be the object diameter projected onto the retina, i.e. angular size of the object (Hoyle, 1957; Lee, 1976). While this relationship holds only for relatively small angles ($\tan\theta \cong \theta$), tau as a cue[1] to the arrival of objects has been persistently suggested because of its great advantage to allow for a TTC estimate without requiring the object's physical distance or its actual size.

In the case of an object moving on an intercept course with the observer, time-to-contact (TTC) can be obtained from local changes in the angular extent of the object and is often referred to as local tau (Tresilian, 1991, 1995). When an object moves towards an observer, but is not on a collision course, the time-to-passage (TTP) of the object to the observer's eye plane can be determined from the relative rate of change of the angular displacement of the object from the observer's line of sight (Hecht & Savelsbergh, 2004). During self-motion, TTP can be estimated relative to the observer's path (track vector), which can in turn be determined from the global optic flow (Gibson, 1950, 1979). In such cases, the rate of change in the angular displacement of the object from the observer's path (typically equivalent to heading direction) relative to it's angular speed (i.e., image velocity) is referred to as global tau (Kaiser & Mowafy, 1993; Tresilian, 1995). For objects approaching with constant speed, image velocity scales with the distance in depth between the object and observer and with the object's offset relative to the observer's track vector.

In the absence of local expansion cues, accurate TTP judgments become increasingly dependent on information about an observer's self-motion. In a study by Kaiser and Mowafy (1993), subjects were asked to make relative TTP judgments of objects with constant size regardless of their depth during simulated self-motion through a cloud of dots. The objects were placed either on opposite sides or the same side of the observers' track vector to differentiate the contributions of global tau versus relative motion of the targets

* Corresponding author at: Department of Biomedical Engineering, Marquette University, P.O. Box 1881, Milwaukee, WI 53201, USA.
E-mail address: scott.beardsley@marquette.edu (S.A. Beardsley).

[1] Some authors, including David Lee, prefer to call tau an invariant, which is thought to be perceptually more immediate than a cue, the latter suggesting cognitive involvement. We use the term cue here without such theoretical implication mostly for the sake of convenience.

0042-6989/$ - see front matter © 2011 Elsevier Ltd. All rights reserved.
doi:10.1016/j.visres.2011.07.003

to estimates of TTP. Kaiser and Mowafy showed accurate and robust use of global tau in the absence of local tau information for relative and absolute TTP judgments made between objects and for individual objects respectively. Performance did not vary with the distance between the targets or the offset of the target from the track vector.

Kerzel, Hecht, and Kim (1999) introduced more extreme object placements including asymmetric placements with regard to the track vector, and found TTP judgments deteriorated. Using a similar experimental setup, target objects were offset from the observers' track vector to varying degrees, placing image velocity cues in conflict with global tau cues. In separate control experiments the relative contribution of self-motion was examined by manipulating observers' ability to estimate the direction of self-motion, and hence global tau, through changes in eye position or by removing the surrounding optic flow entirely. In contrast to global tau predictions, TTP judgments were strongly dependent on the relative offsets between targets and were little affected in cases where the direction of self-motion could not be reliably estimated. They concluded that TTP judgments were driven by the simpler parameter of angular (image) velocity of the objects, suggesting that optic flow from self-motion is not typically utilized in TTP estimates.

Interestingly, several studies have reported a strong dependence of time-to-contact (TTC) judgments on self motion-in-depth (Geri, Gray, & Grutzmacher, 2010; Gray, Macuga, & Regan, 2004; Gray & Regan, 2000), suggesting that object motion and self-motion are integrated in the perception of object movement in depth. The discrepancies between these findings and those of Kerzel et al., may be due to differences in the degree of vection experienced by subjects. Thus, a generalized TTP mechanism that utilizes the flow field to establish tracking (Gray & Sieffert, 2005), might depend on the quality of the optic flow and the degree of self-motion that is induced by the stimulus.

Here we investigate the effect of simulated self motion-in-depth on TTP judgments by varying the coherence of the motion signals present in the optic flow. We systematically removed local tau cues from the display to clarify the role of local image velocity versus global flow in estimates of TTP. Consistent with Kerzel et al. (1999) we show that observers rely on image velocities, rather than global tau, as the primary cue for TTP judgments when local tau information is unavailable. However, unlike Kerzel and colleagues, we identify a dependence of TTP judgments on self-motion, such that biases induced by image velocity cues were systematically reduced as the coherence of the optic flow increased. We discuss these results in the context of a global tau mechanism that contributes to TTP estimates when the observer is in motion.

2. Methods

2.1. Stimuli

Stimuli consisted of random dot kinematograms (RDK) arranged such that they produced a large virtual trapezoidal volume extending 20 m in depth in front of the observer. The RDKs were generated by an Apple Macintosh G5 Power PC and displayed on a Flat Panel LCD Cinema Display. RDK motion sequences were presented in a calibrated gray-scale mode at a screen resolution of 1024×768 pixels. Each RDK simulated 3D cloud of 1248 dots uniformly distributed in a trapezoidal volume extending 260–2060 cm from the observer. Dots were white (79.55 cd/m^2) and displayed against a gray background (10.22 cd/m^2). The dot field was viewed on the display limited by a square aperture on the screen subtending $25° \times 25°$ at a viewing distance of 60 cm. Two red target dots (51.20 cd/m^2) were embedded within the dot cloud on opposite sides of the vertical meridian. Dot size (including targets) was held constant at 2×2 pixels (4×4 arcmin) to eliminate local tau cues.

The motion of the dots within the volume simulated the observer's forward self-motion along a straight-line track vector at a speed of 150 cm/s. In each trial, the direction of simulated self-motion was located at the center of the aperture. Dots that moved outside the trapezoidal volume were randomly assigned to new locations such that the density of the dots inside the 3D volume was held constant (Fig. 1).

The psychophysical variable of interest was the relative difference in the time-to-passage of the target dots ($\Delta\tau$) through the eye plane of the observer. Target dots were placed on opposite sides of the observer's straight-line trajectory and at different depths such that the time-to-passage of the leading target at the end of the motion sequence ranged from 3 to 6 s. The initial simulated depth of one target was set to 1050 cm, 1200 cm or 1350 cm; and based on the $\Delta\tau$ value and whether the target was arriving first (*leading target*) or second (*trailing target*), the initial depth of the other target was assigned. Once placed, the target dots remained visible throughout the 3 s. stimulus presentation and moved toward the observer's eye plane along trajectories and with speeds consistent with the simulated self-motion. The spatial offset of the target dots with respect the direction of self-motion, referred to here as *x*-offset was specified according to the experimental condition being tested (see Section 2.2).

2.2. Experimental procedure

Prior to the start of an experimental session, subjects adapted for 5 min to the background luminance of the monitor display in

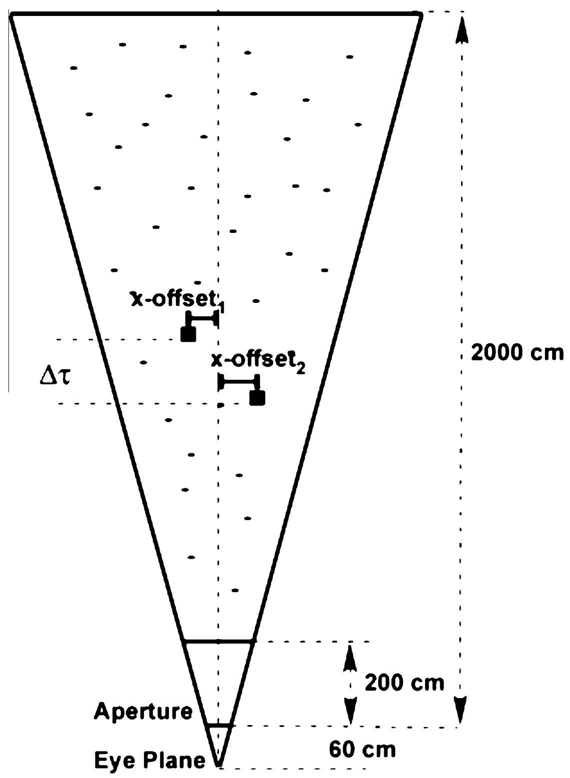

Fig. 1. Schematic of the virtual trapezoidal volume. White dots simulating forward self-motion were randomly distributed between 260 cm and 2060 cm from the observer. The two red target dots (denoted with the symbol '■' here for clarity) were embedded in the flow field and moved with the same speed as the flow field according to their instantaneous position within the volume. The direction of self-motion matched the center of the aperture.

a quiet and darkened room. Each trial consisted of a 3 s RDK stimulus followed by the presentation of a static random dot pattern until the subject made a button press. The static random dot field had the same spatial statistics as the motion sequence but no target dots. This prevented subjects from making judgments based on a static comparison of the final target locations directly, or indirectly via the locations of dots near the targets at the end of the motion sequence.

During the psychophysical task, stimuli were presented binocularly in a two-alternative forced choice (2AFC) paradigm while observers fixated on a small central cross (40×40 arcmin). The subjects' task was to determine which of the two targets would have arrived at their eye plane first, if the motion had continued. Responses were entered by pressing a predetermined button on the computer keyboard. No feedback was provided during the task.

Subjects' performance was examined as a function of the difference between target arrival times, $\Delta\tau$, the initial *x*-offsets of the targets, and the coherence of the self-motion using a three-factor within-subjects design. The difference in arrival times was manipulated by varying the distances in simulated depth between the leading and trailing targets such that $\Delta\tau$ was 0.25 s, 0.5 s, 0.75 s or 1 s. The *x*-offsets for the leading and trailing targets were specified separately at 10 cm, 35 cm or 50 cm, resulting in nine unique combinations of target offsets. At the beginning of the motion, the angular target displacements ranged from 0.37° to 2.98° depending on the initial simulated depths of the targets, placing angular estimates of position well within the small-angle approximation assumed for global tau estimates. The coherence of the optic flow used to simulate self-motion was manipulated by perturbing the 3D trajectories for a proportion of the non-target dots selected randomly in each stimulus frame. Dot trajectories were perturbed by assigning a new trajectory with the same displacement as the original dot trajectory but whose direction angle was selected from a uniform distribution ([0°, 180°] for azimuth angle, [0°, 360°] for elevation angle) (Sikoglu, Calabro, Beardsley, & Vaina, 2010; Watamaniuk, Sekuler, & Williams, 1989). At the most extreme condition of 0% coherence the dot motion was entirely random, thus removing all optic flow and cues to self-motion. At 100% coherence, no dots were randomly repositioned between frames resulting in a stimulus consistent with smooth self-motion toward the dot cloud. In the current experiment, three levels of perturbation were tested corresponding to 0%, 50% and 100% coherence.

In three of the *x*-offset combinations, the targets were offset by the same amount, yielding *symmetric* arrangements with respect to the direction of heading. In the other six combinations, the targets were placed with different horizontal offsets, yielding *asymmetric* arrangements with respect to the track vector. Since the 2D image velocities of the targets can increase with decreasing depth or with increasing eccentricity, a subset of the asymmetric conditions introduced a cue conflict for $\Delta\tau$ judgments based on image velocity. For instance, when the leading target was less eccentric than the trailing target, its *2D* image velocity was smaller than the trailing target, thus producing an *invalid cue*. If observers relied on image velocity alone, their judgments for $\Delta\tau$ is these conditions will be incorrect. When the leading target was more eccentric than the trailing target, the *2D image velocity cue was valid* and would predict correct judgments for $\Delta\tau$.

During the experiment, each combination of $\Delta\tau$ (4) values and *x*-offsets (9) was presented as a separate stimulus condition 24 times across four constant-stimulus blocks (216 trials/block). Within a block, $\Delta\tau$ and *x*-offset combinations were counterbalanced across trials (six trials per $\Delta\tau$, *x*-offset combination). The coherence of the background dots was fixed within each block, and four blocks (864 trials total) were collected for each of three coherence levels (0%, 50%, and 100%). In a separate control condition TTP judgments with only the target dots presented on the display were obtained for the nine *x*-offset combinations with $\Delta\tau$'s of 0.5 and 1 s to control for the effect of background motion in TTP estimates.

2.3. Subjects

Ten subjects (six females, four males, mean age = 22.9 years, SD = ±4.65) participated in the experiments. Seven subjects participated in the primary experiment. Five subjects (two from the primary experiment plus three additional subjects) participated in a secondary experiment to control for the effects of optic flow on TTP performance. All had normal or corrected-to-normal vision. Two subjects, ES and FC, were experienced psychophysical observers. The other eight subjects were unaware of the purpose of the experiments. All participants gave written consent before the start of the experimental sessions in accordance with Boston University's Institutional Review Board Committee on research involving human subjects.

3. Results

We expected to find an influence of the coherence of the optic flow if global flow information is utilized. If, however, observers merely rely on the local image velocity of the targets then global incoherence should not impact performance. Fig. 2 shows the average percent correct performance across seven subjects (±SE) as a function of the difference in arrival times between the two targets ($\Delta\tau$) for the three levels of coherence in the background motion (0%, 50%, and 100%). The results are plotted separately for the targets whose initial locations were symmetric (*x*-offsets equal at 10, 35, and 50 cm) or asymmetric with respect to the track vector. In the asymmetric condition, performance is plotted with respect to the difference in *x*-offsets between the leading and trailing target (Δoffset = −40, −25, −15, 0, 15, 25, 40 cm). For symmetric offsets, performance on the TTP task decreased as the coherence of the background (self-)motion increased. No systematic effects of target displacement from the track vector were observed. When target offsets were asymmetric, coherence had a similar effect on TTP estimates and performance was also biased based on the sign of the difference in *x*-offsets between the leading and trailing targets. When the leading target was closer to the track vector (Δoffset > 0), performance improved relative to symmetric trials. When the trailing target was closer to the track vector (Δoffset < 0), subjects systematically selected the trailing target as closer, biasing percent correct performance toward zero.

The effect of optic flow coherence on performance in the TTP task is shown in Fig. 3 for asymmetric targets. Performance, shown as the mean (±SE) averaged across all $\Delta\tau$ values for seven subjects, decreased with increasing coherence when the leading target had the larger *x*-offset (Δoffset < 0) and increased (was less biased) when the trailing target had the larger *x*-offset (Δoffset > 0). The dependence of TTP judgments on coherence suggests that subjects utilize global tau information when it is available, although not always to the benefit of the observer (i.e., Δoffset > 0).

Separate repeated measures analysis of variance (ANOVA) were performed for symmetric and asymmetric targets with percent correct performance as the dependent variable to examine the effect of coherence and *x*-offset on TTP performance. Mauchly's test indicated that the assumption of sphericity was valid for most comparisons. For cases in which sphericity could not be assumed, the Greenhouse–Geisser correction for degrees of freedom was used in subsequent comparisons. Post hoc analyses of the estimated marginal means (±1 SE) were performed on all factors (coherence, *x*-offset and $\Delta\tau$) to characterize the contributions of global tau (vis-à-vis the optic flow coherence), and 2D image velocity (vis-à-vis the relative difference in *x*-offsets) to estimates of

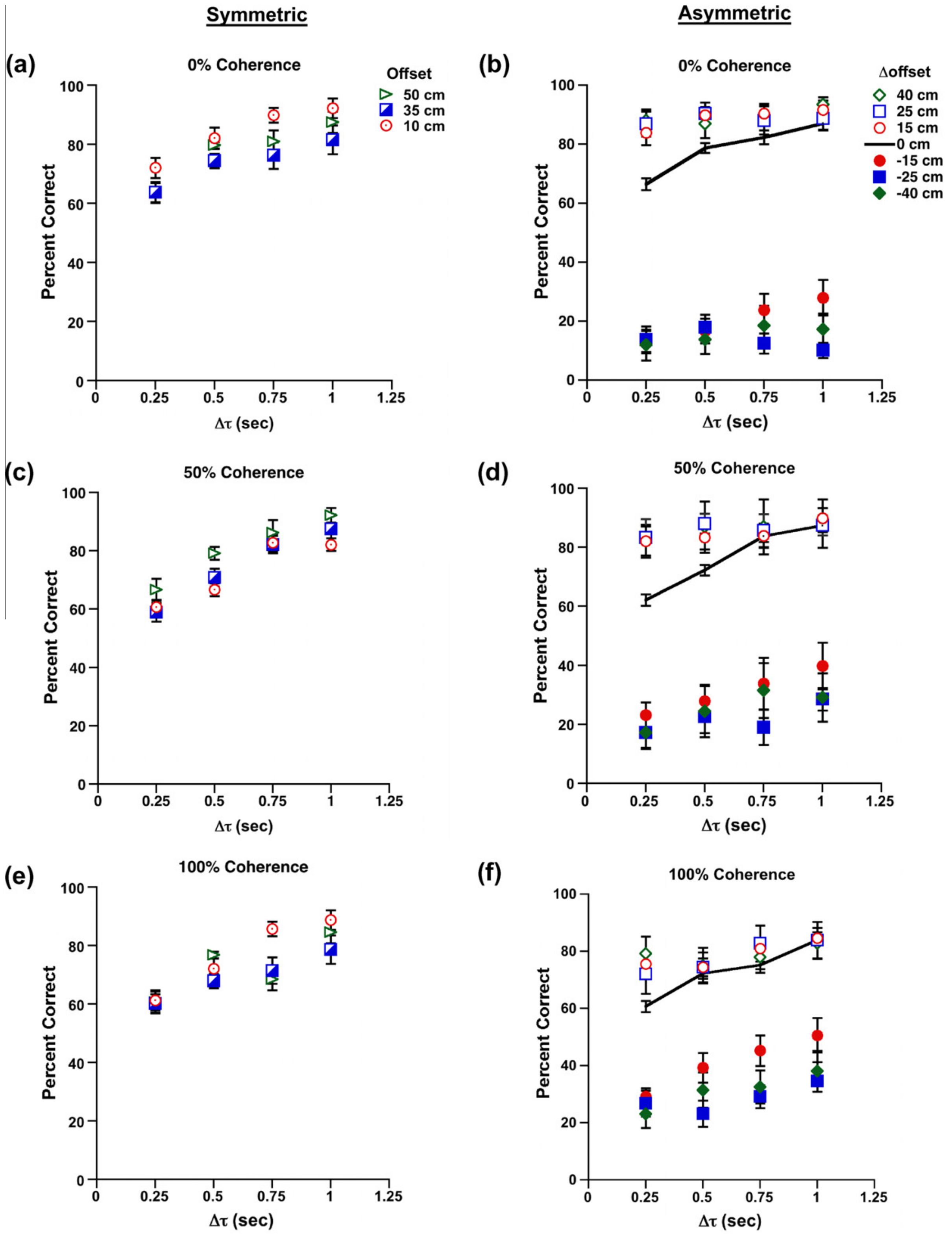

Fig. 2. The average percent correct values across seven observers as a function of difference in arrival times of two targets ($\Delta\tau$). Left (a, c, e) and right (b, d, f) columns denote the performance for the trials in which the targets were symmetrically and asymmetrically arranged, respectively. In the right column (b, d, f), data is segregated in terms of the relative difference between the initial target *x*-offset values, i.e. leading target initial *x*-offset (10, 35, or 50 cm) minus trailing target initial *x*-offset (10, 35, or 50 cm). The dotted lines refers to the conditions where the relative difference between the initial target *x*-offset values is zero, i.e. the average across different *x*-offset conditions for the data shown on the left column. Each row illustrates the different levels of coherence for the optic flow field dots; (a and b) for 0%, (c and d) for 50%, (e and f) for 100%. Error bars correspond to the standard error across observers.

TTP. A Bonferroni correction for multiple comparisons was applied to all pair-wise tests.

For symmetric targets, a three-way ($3 \times 3 \times 4$) ANOVA was performed with *x*-offset (10, 35, and 50 cm), coherence (0%, 50%,

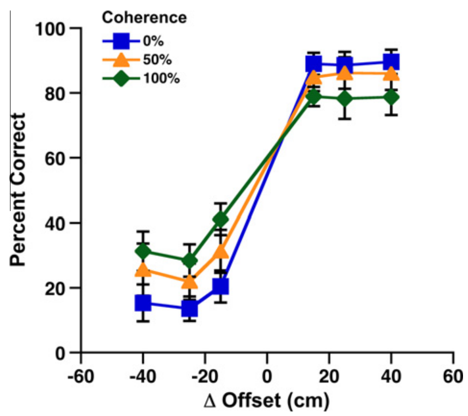

Fig. 3. Percent correct performance for TTP judgments as a function of the relative *x*-offset (leading–trailing) for 0%, 50% and 100% coherent flow conditions. Performance is shown as the mean (±SE) averaged across all $\Delta\tau$ values for seven subjects.

100%), and $\Delta\tau$ (0.25, 0.5, 0.75, 1 s), as within-subject factors. Across subjects, there were significant main effects of coherence ($F_{2,12} = 6.11$, $p < 0.05$), *x*-offset ($F_{2,12} = 19.56$, $p < 0.001$), and $\Delta\tau$ ($F_{1.36,8.17} = 53.32$, $p < 0.001$ corrected). No significant interactions were found between factors.

Within-subjects contrasts revealed a small linear decrease in performance on the TTP task with coherence ($F_{1,6} = 7.33$, $p < 0.05$), although pairwise comparisons were not significant (0%: 78.67 ± 1.84, 50%: 76.34 ± 1.46, 100%: 73.03 ± 1.77, $p > 0.1$). TTP performance increased linearly with $\Delta\tau$ ($F_{1,6} = 85.40$, $p < 0.001$), with significant pairwise comparisons between all levels (0.25 s: 63.1 ± 1.85, 0.5 s: 74.40 ± 1.40, 0.75 s: 80.42 ± 2.3, 1 s: 86.11 ± 1.669, $p < 0.05$). In the case of *x*-offset, pairwise comparisons showed significant differences between all levels (10 cm: 80.7 ± 1.95, 35 cm: 72.17 ± 1.48, 50 cm: 75.15 ± 1.41, $p < 0.05$), although there was no consistent trend.

For asymmetric targets, a four-way (2 × 3 × 3 × 4) ANOVA was performed with the sign of the difference between leading and trailing target *x*-offsets (Δoffset sign; + or −), amplitude of the *x*-offset difference (Δoffset amplitude; 15, 25, 40 cm), coherence (0%, 50%, 100%), and $\Delta\tau$ (0.25, 0.5, 0.75, 1 s), as within-subjects factors. Across subjects, there were significant main effects of coherence ($F_{2,12} = 6.18$, $p < 0.05$), Δoffset sign ($F_{1,6} = 89.55$, $p < 0.001$), Δoffset amplitude ($F_{2,12} = 5.63$, $p < 0.05$), and $\Delta\tau$ ($F_{3,18} = 11.19$, $p < 0.001$), on TTP judgments. The two-way interactions between coherence and Δoffset sign ($F_{2,12} = 7.95$, $p < 0.01$), and Δoffset sign and $\Delta\tau$ ($F_{3,18} = 3.33$, $p < 0.05$) were also significant. No significant effects were observed among the remaining interactions, including coherence and Δoffset amplitude ($F_{4,24} = 0.88$, $p = 0.49$), coherence and $\Delta\tau$ ($F_{6,36} = 1.86$, $p = 0.11$), and all higher order (three and four-way) interactions.

Within-subjects contrasts revealed linear effects of coherence (0%: 52.73 ± 0.86, 50%: 55.95 ± 1.39, 100%: 56.11 ± 1.38), and $\Delta\tau$ (0.25 s: 50.49 ± 0.57, 0.5 s: 53.70 ± 1.23, 0.75 s: 56.27 ± 1.80, 1 s: 59.26 ± 1.85) on TTP judgments ($F_{1,6} > 8.6$, $p < 0.05$),[2] but not Δoffset amplitude (15 cm: 57.56 ± 1.78, 25 cm: 52.80 ± 0.98, 40 cm: 54.42 ± 1.17). Coherence also had a linear modulatory effect on Δoffset sign and $\Delta\tau$ ($F_{1,6} > 8.14$, $p < 0.029$) but not Δoffset amplitude ($F_{1,6} = 2.93$, $p = 0.137$). No other linear contrasts were significant. Pairwise comparisons of the effect of Δoffset sign were highly significant (+Δoffset: 84.44 ± 3.02, −Δoffset: 25.42 ± 3.54, $p < 0.01$), and were coupled with the effects of coherence and Δoffset value. When the leading target had a smaller *x*-offset (i.e., closer to the track vector, Δoffset < 0) performance improved with coherence; with incoherent self-motion (0% coherence) significantly worse than fully coherent self-motion (100% coherence) ($p < 0.05$). When the leading target had a larger *x*-offset than the trailing target (Δoffset > 0), performance degraded with coherence; with fully coherent self-motion (100% coherence) worse than with incoherent motion (0% coherence) ($p < 0.05$). Subsequent contrast analysis using signed Δoffsets showed a highly significant linear interaction between coherence and Δoffset ($F_{1,6} = 136.98$, $p < 0.0001$), indicating a strong interaction between coherence and the relative *x*-offset between leading and trailing targets.

When the initial eccentricity (*x*-offset) of the leading target was more peripheral than the trailing target, TTP judgments were well above chance (Fig. 3; Δoffset > 0). In these cases the 2D image velocities presented a *valid* information cue. Conversely, when the initial eccentricity of the trailing target was more peripheral than the leading target, TTP judgments were well below chance. In these cases the 2D image velocities presented an *invalid* information cue. Observers were unable to discount this invalid cue and thus produced more errors leading to a systematic bias in relative TTP judgments. Together these results corroborate those reported previously by Kerzel et al. (1999), supporting the notion that observers rely heavily on the 2D image velocities of the targets (possibly in conjunction with their final 2D eccentricity) to estimate TTP. However, it does not fully address the impact of the global (self)-motion on TTP estimates.

To disambiguate the effects of background motion we repeated the experiment replacing the intermediate coherence condition with no-background trials. That is, either the two target dots were shown in isolation (with no background dots), within a 0%-coherence cloud of dots or within a 100%-coherence cloud of dots. Subjects were tested for two levels of $\Delta\tau$ = 500 and 1000 ms and seven levels of Δoffset (symmetrically at 10, 35, and 50 cm and asymmetrically at ±15 cm, ±40 cm). All other aspects of the methods remained the same. Five subjects (two male, three female) participated in the experiment (two from the initial experiment and three new subjects). Fig. 4 shows the average percent correct performance across subjects as a function of the relative offset difference.

In the symmetric condition, a three-way (3 × 2 × 3) ANOVA was performed with coherence ('no-background', 0%, 100%), $\Delta\tau$ (0.5 s, 1 s), and *x*-offset (10, 35, and 50 cm) as within-subjects factors. Across subjects there was a significant main effect of coherence ($F_{2,8} = 8.94$, $p < 0.05$) but not *x*-offset ($F_{2,8} = 2.19$, $p = 0.17$) or $\Delta\tau$ ($F_{1,4} = 0.46$, $p = 0.54$). The two-way interaction between coherence and $\Delta\tau$ ($F_{2,8} = 15.74$, $p < 0.01$), and the three-way interaction between coherence, $\Delta\tau$, and *x*-offset ($F_{4,16} = 3.58$, $p < 0.05$) were also significant. No significant effects were observed among the remaining interactions.

In the asymmetric condition, a four-way (3 × 2 × 2 × 2) ANOVA with coherence ('no-background', 0%, 100%), Δoffset value (15 cm, 40 cm), sign (+/−) and $\Delta\tau$ (0.5 s, 1 s) as within-subjects factors revealed significant main effects of Δoffset sign ($F_{1,4} = 259.24$, $p < 0.001$; Fig. 4) and coherence ($F_{2,8} = 6.45$, $p < 0.05$; 'no-background': 51.72 ± 0.89, 0%: 53.28 ± 1.43, 100%: 56.39 ± 0.77) but not $\Delta\tau$ ($F_{1,4} = 3.83$, $p = 0.12$; 0.5 s: 52.08 ± 0.74, 1 s: 55.51 ± 1.45). The only significant interaction occurred between coherence and $\Delta\tau$ ($F_{2,8} = 5.19$, $p < 0.05$), with the larger $\Delta\tau$ resulting in a larger percent correct performance change between 'no-background', 0%, and 100% coherence conditions. As in Fig. 3, a consistent interaction between motion coherence and the sign of the *x*-offset was observed (Fig. 4), such that performance increased with the addition of background motion (and coherence) for asymmetric targets resulting in an invalid cue (Δoffset < 0; 'no-background': 10.52 ± 4.88, 0%: 17.60 ± 4.38, 100%: 25.80 ± 2.66). Similarly,

[2] Inequalities are used here to define the most conservative, least significant, bounds (both in the *t*- and *p*-values) when referring to significant effects across multiple tests with the same degrees of freedom.

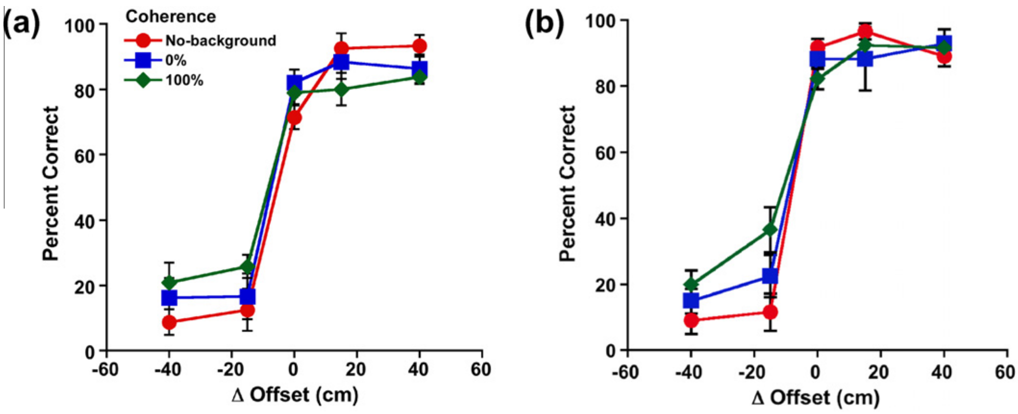

Fig. 4. Percent correct performance for TTP judgments as a function of the relative *x*-offset (leading–trailing) for the 'no-background', 0% and 100% coherent flow conditions. Performance is shown as the mean (±SE) averaged across five subjects for $\Delta\tau$ values of (a) 0.5 and (b) 1.0 s. For clarity, the average performance across subjects in the symmetric condition (*x*-offset = 0), is collapsed to a single estimate across the three offsets (10, 35, and 50 cm) tested.

performance decreased with the addition of background motion (and coherence) for asymmetric targets offsets resulting in a valid cue (Δoffset > 0; 'no-background': 92.92 ± 3.11, 0%: 88.96 ± 5.38, 100%: 86.98 ± 2.33), although the combined interaction was not significant across the five subjects tested ($F_{2,8} = 1.96$, $p = 0.2$).

Interestingly, observers continued to perform above chance without a background, indicating a reliance on image velocity to perform the task. The presence of random background motion (i.e., 0% coherence), added no support for the extraction of a global flow direction, yet performance improved marginally when the image velocity cue was invalid. Fully coherent background (self-)motion tended to make TTP judgments more robust in the presence of invalid velocity cues.

Overall, performance improved with an increase in the difference between target arrival times ($\Delta\tau$), for symmetric offset configurations. When the target offsets were asymmetric such that the 2D image velocity cue provided valid information, performance was well above chance. Conversely when the image velocity cue provided conflicting information in comparison to the arrival times of the targets, performance was well below chance. This suggests that observers relied heavily on the optical speeds of the targets. However, the dependence of TTP judgments on the coherence of the self-motion also indicates that optic flow played a role in TTP estimates. When the image velocity cue provided valid information, performance was at its best when optic flow due to self-motion was incoherent (0% coherence), or not present. Conversely, when the image velocity cue provided invalid information, misidentification decreased when the coherence of optic flow due to self-motion increased from 0% to 50% to 100%. These results suggest that the reliance on image velocity increased when the optic flow did not provide useful reference information, and suggests the use of additional cues and or mechanisms when meaningful self-motion is present.

4. Discussion

In this study, we investigated how the human visual system processes TTP judgments when local tau information is not available. Previous psychophysical work on TTC judgments reported the involvement of optic flow in tau judgments (Gray & Regan, 2000; Gray et al., 2004), and specifically the importance of global tau for TTP judgments in the absence of local tau information (Kaiser & Mowafy, 1993). A study by Kerzel et al. (1999), has contradicted this view by showing that global tau is not needed for TTP judgments when local tau cues are absent. They showed that relative differences in the image velocities of targets can explain observers' performance in estimating TTP when local tau cues are not available. Here, by manipulating the available signal information within the optic flow, we show that human observers do utilize optic flow for TTP judgments under certain conditions and not always to their advantage.

In general, for objects approaching with constant speed, the rate of change in angular displacement, i.e. 2D image velocity, is larger if the distance between the observer and the object is smaller or if the x displacement, i.e. *x*-offset of the object from the direction of motion is larger. In our experimental set-up, the arrival times were a function of the initial simulated depths of the objects. Note that the initial *x*-offset value associated with a given target was irrelevant for its arrival time, but the final target eccentricity was inversely correlated with arrival time. Thus, while *x*-offset, as a 3D metric, was uncorrelated with arrival time, the final target eccentricity of the 2D projection onto the display, and eye, was correlated with arrival time. Therefore observers could make their TTP judgments by reconstructing the depth information and thus possibly employing global tau information, or they could perform above chance by employing 2D image velocity (or even position) information provided by the final *x*-offsets of the targets. The latter could be thought of as a heuristic to judge objects that move retinally faster as passing sooner. Such an image velocity heuristic will lead to correct TTP judgments when targets are arranged symmetrically around the track vector. However, for asymmetric targets this heuristic does not work reliably. For example, an object closer to the observer with a small *x*-offset from the direction of motion may have a smaller image velocity than an object further away from the observer with a larger *x*-offset from the direction of motion. A different, even simpler heuristic may be used in this case. Observers might take the more eccentric target to be closer to them and hence choose it as contacting earlier.

Similar to Kerzel et al. (1999), we have shown that observers rely mostly on image velocities for making TTP judgments when the local tau information is not available. In other words, more eccentric targets with higher image velocities were consistently perceived to have smaller TTP values than targets with lower image velocities. They further suggested that observers may also rely on image acceleration in addition to image velocity to judge TTP (Kerzel, Hecht, & Kim, 2001). In our experiment image acceleration was fixed throughout the stimulus to eliminate potential confounds with motion coherence. As coherence decreased, image speeds and accelerations were maintained across the motion stimulus by using the same frame-wise displacements while randomizing the direction of "noise" dots' trajectories. Thus, the current results do not directly address the question of using image acceleration in conjunction with image velocity.

Kerzel and colleagues interpreted their results as the visual system being unaware of the global tau cue and simply adopting a less expensive strategy based on image velocity (Kerzel et al., 1999). The bias in subjects TTP judgments toward the more eccentric target, supports the use of image velocity as the main information cue in solving the task, however, the dependence on coherence also shows that observers utilize global tau when optic flow information is available. By changing the coherence of the non-target dots in the flow field, we were able to vary the global motion information from being maximally informative (with 100% coherence: an ideal observer using global tau should make no errors) to being utterly uninformative (with 0% coherence: global tau is no longer available). With this graded manipulation of the information content in the optic flow, our results show that the velocity heuristic is not used exclusively. Interestingly, coherent motion attenuates the velocity heuristic. That is, observers do benefit from global tau information when the velocity heuristic is mistaken but they are misled by the optic flow in those cases where the velocity heuristic makes a correct prediction.

In order to illustrate the conditions under which the global tau information was consolidated in solving the TTP task in the absence of local expansion cues, we sampled a range of target *x*-offset values for leading and trailing targets. Fig. 5a shows the difference between leading and trailing targets' global tau values when $\Delta\tau$ is 0.5 s. The values are correctly centered at the arrival time difference of 0.5 s, and show little variation (<0.03 s) across the range of target offsets sampled. Fig. 5b shows the difference between the leading and trailing targets' 2D image velocities for $\Delta\tau$ values of 0.25 s, 0.5 s, 0.75 s and 1 s. When the image velocity difference was positive, the leading target's initial *x*-offset value was greater than the trailing target's initial *x*-offset value, resulting in a valid 2D image velocity cue. When the image velocity difference was negative, the trailing target's initial *x*-offset value was greater than the leading target's initial *x*-offset value, resulting in an invalid 2D image velocity cue.

Subjects had difficulty detecting global tau differences, which may explain their reliance on the image velocity information rather than global tau information. However the reversal of infor-

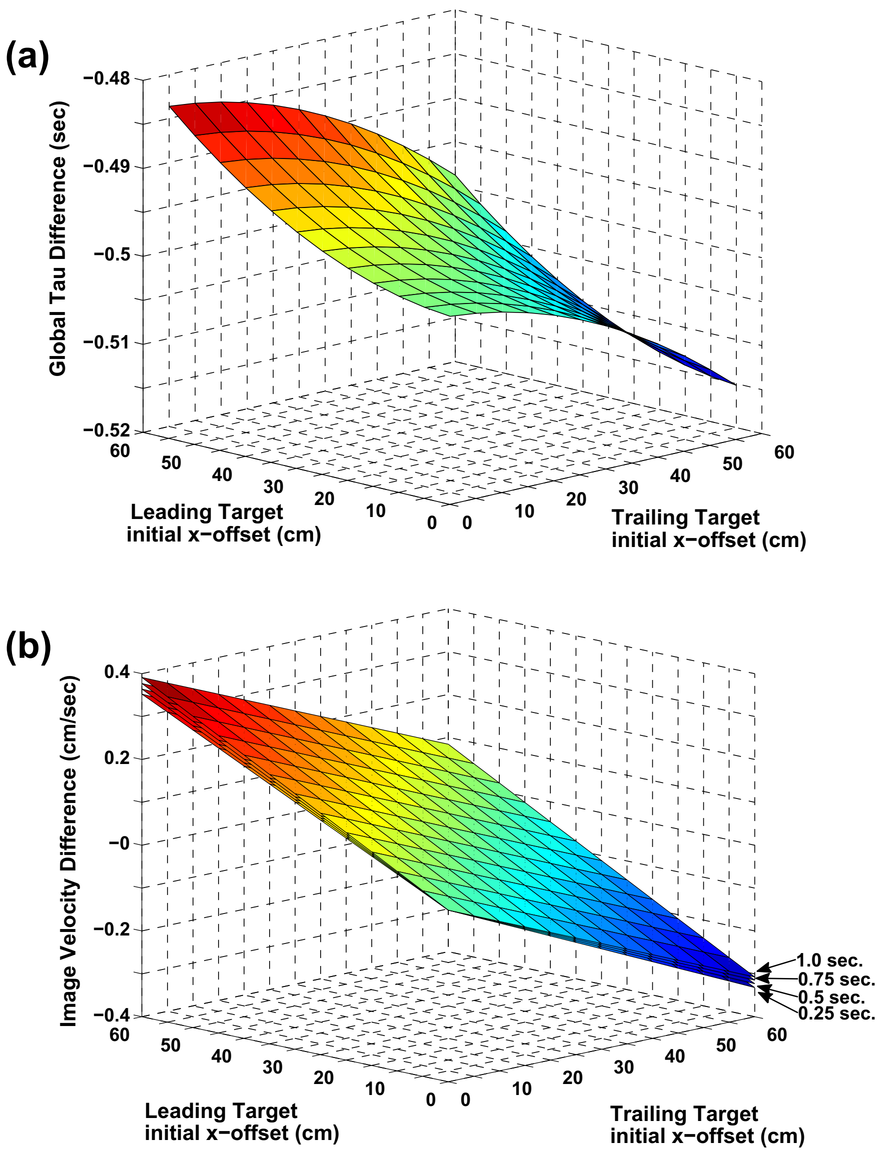

Fig. 5. (a) Differences in global τ values for a sampled distribution of leading and trailing target *x*-offsets, for $\Delta\tau = 0.5$ s. (b) Differences in the 2D image velocity values for a sampled distribution of leading and trailing target *x*-offsets, for $\Delta\tau$ values of 0.25 s, 0.5 s, 0.75 s and 1 s. Differences between relative amplitudes within each plot are denoted by the surface shading.

mation within Fig. 5b illustrates the limited reliability of the velocity heuristic. The visual system seems to sense this reliability problem but is unable to replace the heuristic with a global flow field analysis. Instead, it merely attenuates the heuristic.

Fig. 2 also illustrates that performance changes due to difference in targets' arrival times, i.e. $\Delta\tau$ values, for symmetric configurations of targets; suggesting the possible use of global tau. For the case of asymmetric target configurations, the slope of performance as a function of $\Delta\tau$ increased with the increase in coherence values. This change suggests a shift from the easily detectable but non-robust 2D image velocity cue to a more robust global tau cue.

5. Conclusion

In summary, this work reconciles two competing notions of what information is used to judge time-to-passage in the absence of local tau information. On the one hand, it has been suggested that a global flow field analysis is being performed by default. On the other hand, less costly perceptual heuristics based on simpler 2D cues of retinal velocity or position have been proposed. By manipulating the available signal information within the optic flow to the point where coherent flow was no longer present, we have demonstrated that both optic flow information as well as 2D cues are utilized in a flexible manner. Observers appear to employ an economic strategy to supplement the 2D estimates with the more costly global optical flow information whenever the 2D information appears unreliable. However, the economical gain of this flexible strategy appears to come at the price of potential error when misleading 2D cues are used or optic flow is perturbed.

Acknowledgments

This work was supported by NIH Grant R01NS064100 to L.M.V. and S.A.B. Co-author H.H. was funded by Deutsche Forschungsgemeinschaft (Sachbeihilfe HE 2122/6-1: Kontaktzeitschätzung im Kontext).

References

Geri, G., Gray, R., & Grutzmacher, R. (2010). Simulating time-to-contact when both target and observer are in motion. *Displays, 31*(2), 59–66.

Gibson, J. J. (1950). *The perception of the visual world*. Boston: Houghton Mifflin.

Gibson, J. J. (1979). *The ecological approach to visual perception*. Boston: Houghton Mifflin.

Gray, R., Macuga, K., & Regan, D. (2004). Long range interactions between object-motion and self-motion in the perception of movement in depth. *Vision Research, 44*(2), 179–195.

Gray, R., & Regan, D. (2000). Simulated self-motion alters perceived time to collision. *Current Biology, 10*(10), 587–590.

Gray, R., & Sieffert, R. (2005). Different strategies for using motion-in-depth information in catching. *Journal of Experimental Psychology: Human Perception and Performance, 31*(5), 1004–1022.

Hecht, H., & Savelsbergh, G. J. P. (2004). Theories of time-to-contact judgment. In H. Hecht & G. J. P. Savelsbergh (Eds.), *Time-to-contact*. Amsterdam: Elsevier–North-Holland.

Hoyle, F. (1957). *The black cloud*. London: Heineman.

Kaiser, M. K., & Mowafy, L. (1993). Optical specification of time-to-passage: Observers' sensitivity to global tau. *Journal of Experimental Psychology: Human Perception and Performance, 19*(5), 1028–1040.

Kerzel, D., Hecht, H., & Kim, N. (1999). Image velocity, not tau, explains arrival-time judgments from global optical flow. *Journal of Experimental Psychology: Human Perception and Performance, 25*(6), 1540–1555.

Kerzel, D., Hecht, H., & Kim, N. G. (2001). Time-to-passage judgments on circular trajectories are based on relative optical acceleration. *Perception and Psychophysics, 63*(7), 1153–1170.

Lee, D. N. (1976). A theory of visual control of braking based on information about time-to-collision. *Perception, 5*(4), 437–459.

Regan, I. I., & Gray, I. I. (2000). Visually guided collision avoidance and collision achievement. *Trends in Cognitive Science, 4*(3), 99–107.

Sikoglu, E. M., Calabro, F. J., Beardsley, S. A., & Vaina, L. M. (2010). Integration mechanisms for heading perception. *Seeing and Perceiving, 23*(3), 197–221.

Tresilian, J. R. (1991). Empirical and theoretical issues in the perception of time to contact. *Journal of Experimental Psychology: Human Perception and Performance, 17*(3), 865–876.

Tresilian, J. R. (1995). Perceptual and cognitive processes in time-to-contact estimation: Analysis of prediction–motion and relative judgment tasks. *Perception and Psychophysics, 57*(2), 231–245.

Watamaniuk, S. N., Sekuler, R., & Williams, D. W. (1989). Direction perception in complex dynamic displays: The integration of direction information. *Vision Research, 29*(1), 47–59.