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Image Velocity, Not Tau, Explains Arrival-Time Judgments From Global Optical Flow

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The time-to-passage (TTP; i.e., the time) until an object passes an observer is optically specified by global tau, a variable that operates on the expansion rate of the angle subtended by an object relative to the observer's heading. M. K. Kaiser and L. Mowafy (1993) provided evidence for observers' sensitivity to global tau in a 3-D cloud of point lights. This interpretation is challenged, and it is suggested that TTP judgments are based on a related but much simpler variable, the image velocity of the object. The present study reexamined several factors that are relevant for the extraction of global tau. When global tau and image velocity were brought into conflict by varying the lateral offsets of the targets, observers showed a strong tendency to rely on the latter variable. Other factors that are supposed to affect TTP judgments only if observers relied on global tau, such as flow-field density and gaze-movement angle, did not affect performance.

Information about time-to-contact (TTC) of an approaching object is essential in many skilled activities such as hitting or catching a ball. For other activities, time-to-passage (TTP) until the object passes the observer is crucial, as, for example, in the case of a speeding motorcyclist on a multiple-lane highway who needs to determine which one of two cars ahead he or she will pass first. TTC is thought to be directly derived from the instantaneous rate of change of retinal object size (Lee, 1976; Lee & Reddish, 1981). Likewise, TTP has been suggested to be directly perceived by use of the relative rate of change of the angle between the direction of motion of the observer (heading) and the position of the target object (Kaiser & Mowafy, 1993; Tresilian, 1991; see our Figure 1). TTC judgments are hypothesized to exploit local within-objects size changes, also referred to as "local tau." TTP judgments, on the other hand, are hypothesized to exploit the changing angular separation between object position and direction of movement, also referred to as "global tau" (Tresilian, 1991). In this article we report six experiments that cast doubt on the claim that observers use global tau when making TTP judgments (Kaiser & Mowafy, 1993). Rather, the present data show that judgments are influenced by the simpler variable of image velocity, that is, the optical speed at which the target travels. Thus, in the case of a display containing two moving dots, it is predicted that observers judge the faster dot to be closer to them. We show that image velocity is not only a competitive predictor for TTP judgments but that it may also even override global tau information. Information about the observer's heading direction does not appear to be instrumental in judging TTP.

Global Tau

Lee (1976; Hoyle, 1957) demonstrated that the TTC with an approaching object is given by a single optical variable, tau. *Tau* refers to the instantaneous rate of change in the visual extent of the object relative to the extent of the instantaneous image. Tresilian (1991) distinguished between two varieties of local tau information that could be used. Local tau, Type 1, is defined as the instantaneous angular extent of an approaching object divided by the instantaneous rate of change of that angle. Local tau, Type 2, is derived similarly but operates on two points on the surface of the object, not on the entire object image. We refer to the rate of change of the angular extent of the entire image or parts of the object as "local expansion." The two local types of tau give valid estimates of TTC for objects on a collision course. For off-axis approaches (TTP), global tau is also available. It is defined as the angular extent between an object and the observer's direction of motion divided by the rate of change of that angle. Thus, the word *global* refers to the fact that the

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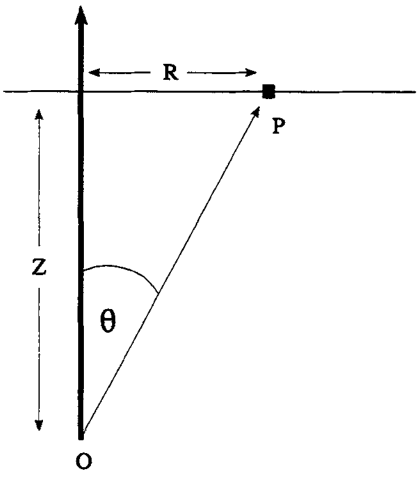

Figure 1. Schematic drawing of a passage event. The observer, O, travels at constant velocity along the direction of motion. An object, P, is offset by some distance, *R*, from the observer's direction of motion. At time *t*, the object is at some distance, *Z*, from the observer. The time-to-passage of the object at time *t* is specified by dividing the angle between object and direction of motion (θ) by the rate of change of that angle ($\delta\theta/\delta t$). The relative rate of change of θ, $\theta/(\delta\theta/\delta t)$, is referred to as global tau. The rate of change of θ, $\delta\theta/\delta t$, is referred to as global expansion. The rate of global expansion is identical to the image velocity of the object. For constant-velocity approaches, the rate of change of θ is larger (a) the smaller the distance between object and observer, *Z*, and (b) the larger the offset from the direction of motion, *R*. In contrast, global tau is unaffected by the size of *R*.

direction of motion has to be extracted from global flow-field information before a TTP estimate can be made. For the purpose of isolating global tau, local tau information of Types 1 and 2 can be eliminated from the stimulus, but information about the direction of motion has to be made available. Simulated observer motion through a cloud of extensionless point lights that give rise to an optic flow field serve this purpose (Kaiser & Hecht, 1995; Kaiser & Mowafy, 1993). Within such a display, the direction of motion is specified by the focus of expansion (FOE; Gibson, 1950, 1966). Thus, global tau operates on the angle between the FOE and the object.

Underlining its evolutionary importance, tau has been shown to affect the behavior of species other than humans (e.g., Lee & Reddish, 1981; Schiff, Caviness, & Gibson, 1962; Wang & Frost, 1992). Also, TTC and TTP situations can be successfully simulated on flat-screen displays, and they lead to reliable temporal estimates in human observers (e.g., Bootsma & Oudejans, 1993; DeLucia & Novak, 1997; DeLucia & Warren, 1994; Kaiser & Hecht, 1995; Kaiser & Mowafy, 1993; Schiff & Detwiler, 1979; Schiff & Oldak, 1990; Simpson, 1988; Todd, 1981). However, the relative and absolute judgment tasks used in these studies may reflect cognitive processing and may differ in a number of ways from interceptive action (Tresilian, 1995).

According to Kaiser and Mowafy (1993), the following competencies are necessary for the use of global tau:

1. The observer's visual system must be able to determine the direction of motion. For linear movement, the direction of motion is specified by the FOE (Gibson, 1950, 1966). For linear forward motion, Warren, Morris, and Kalish (1988) demonstrated that performance declines in the absence of a global flow field. Detection of the direction of egomotion is therefore supposed to depend on the availability of global flow-field information. Tresilian (1995) hypothesized that the main source of uncertainty in estimating global tau is the uncertainty in FOE location. He presented estimations of TTP difference thresholds that take into account thresholds for the detection of the direction of motion (heading thresholds) as determined by Warren et al. (1988). Consistent with the assumption that FOE location is important for TTP judgments, his estimations of TTP difference thresholds fit Kaiser and Mowafy's (1993) data reasonably well.
2. The observer must able to perceive the angle between the direction of motion and an object point. This competency might be compromised at large angular separations when it is difficult to follow both target and FOE.
3. The global rate of angular expansion must be available to the perceptual system. In general, the global optical expansion of a target moving toward the observer is determined by two factors. The first factor is the lateral offset of the target from the direction of motion. The expansion of a target with a large offset from the direction of motion is greater than the expansion of a target close to the direction of motion traveling the same distance toward the observer. The second factor is the distance of the target from the observer. The optical expansion rate of a target that is nearer to the observer is larger than the expansion rate of a target with the same offset that is farther away from the observer.

Because of the heterogeneous terminology used in association with tau, note the differences between global tau, rate of expansion, and image velocity: Optical expansion can be derived from the angle between direction of motion and object position (as in the global tau formula). However, it can also be derived from the angle between the object and an arbitrary reference point, such as the angle between the object and the edge of the screen. Strictly speaking, the angular difference between two successive positions of the object suffices to compute the global expansion rate. In other words, the angular image velocity of an expansionless dot yields the same values as does the expansion rate of the angle between the dot and the observer's direction of motion. Therefore, information about the expansion rate can either be determined with reference to the direction of motion or without external reference marks. The expansion rate of an object is in principle reference free and does not require global information. It is therefore not "global" in a strict sense. This does not, of course, preclude the possibility that global parameters are used. Because the numerical values for global expansion and image velocity are identical the term *global expansion* merely expresses a conceptual preference. Global tau, on the other hand, requires processing of the angular extent between the object and direction of motion. If expansion information is gained with reference to an arbitrary reference point, the respective angle will not give TTP if entered into the global tau formula.

Doubts About Global Tau

Despite the evidence in favor of the tau hypothesis, theoretical and empirical arguments have been developed that show the insufficiency of tau as a variable guiding skilled activities. In a critical review of studies of interceptive timing in natural contexts, Wann (1996) suggested that temporal control could have been achieved using a relative distance estimate. Thus, the simpler variable of relative distance rather than its derivative may guide TTC judgments. Tresilian (1991) demonstrated formally that tau is insufficient for the accurate timing of interceptive acts. In particular, the mathematical derivation of tau does not incorporate interceptions that occur at a distance from the eye plane. Catching a ball should be impossible in many situations because of the timing error introduced by an outstretched arm (however, see Wann, 1996, for a different view). Moreover, tau does not apply to accelerated approaches because constant approach velocity is always assumed. Empirically, and in support of a tau-based strategy, observers have been shown to be unable to factor acceleration into their time-to-arrival (TTA) judgments (Kaiser & Hecht, 1995; Lee, Young, Reddish, Lough, & Clayton, 1983).

In addition to the demonstrated insufficiency of tau, TTA judgments are known to be mediated by several variables that are not related to tau, such as the absolute amount of optical magnification (Kebeck & Landwehr, 1993), changing target vergence (Heuer, 1993), and perceived velocity (Smeets, Brenner, Trébuchet, & Mestre, 1996). Furthermore, DeLucia (1991; DeLucia & Warren, 1994) showed that relative size as a static depth cue supersedes motion-based depth information for objects on a collision trajectory. Similarly, observers showed an overreliance on relative distance information when judging relative arrival times in the transverse plane (Law et al., 1993). In a recent study, DeLucia and Novak (1997) examined the effects of set size in a relative judgment task in which observers had to indicate which of two to eight objects approaching the observer would be the first to pass. The objects showed both local and global expansion. They noted a larger drop in observers' performance when global expansion rate contradicted TTA information than when local expansion rate contradicted TTA information. However, their preliminary conclusion that global optical expansion is a particularly effective cue in relative judgments needs further validation for two reasons.

First, global and local expansion were not systematically varied. For the first- and next-arriving object (DeLucia & Novak, 1997, Table 2), both the absolute values and the range of values were larger for global expansion (2.2°–5.3°/s) than for local expansion rates (0.8°–1.2°/s). Second, the displays simulated objects approaching a stationary observer, not an observer moving through a stationary environment. Thus, the direction of motion was not specified by the FOE. Rather, the "primary line of sight" was specified by the intersection of the boundary lines that separated the locations of the objects. It is not clear whether observers were instructed to fixate on this point or what other reason might have justified the term *line of sight.* Most certainly, this point did not represent a singularity in the flow field. It remains an open question whether observers identified the line intersection as the axis of approach of the objects, which is necessary for using global tau. Thus, observers' failure to use global tau is not surprising given that information about the direction of observer motion was not present in the displays.

Image Velocity

For the following reasons, we hypothesize that image velocity, but not global tau, is used to make TTP judgments: The use of global tau presupposes processing of all three necessary components, as laid out by Kaiser and Mowafy (1993). However, even if the three variables are separately available to the observer, global tau might not be used given that it operates on the ratio of the angle between object and direction of motion and the instantaneous rate of change of that angle. Although it has been argued that perception of TTA via tau is economical because it does not require the perception of either distance or velocity, it still involves processing of three single optical variables and the relations among the three. This perceptual competency might be prone to errors. In particular, difficulties might arise from the contributions that both offset from the direction of motion and distance to the observer have on the angular image velocity. Thus, it is more plausible to hypothesize that observers use the simpler variable of image velocity that does not require identification of the direction of motion. In natural-approach scenarios, the image velocity of approaching objects increases as the distance between object and observers shrinks. Consequently, observers might map large-image velocity onto the judgment that the object is close. However, the validity of image velocity as a cue to depth is limited. Objects close to the observer with a small offset from the direction of motion may have a smaller image velocity than objects far from the observer with a large offset. Thus, reliance on image velocity will lead observers to mistake far objects with large offsets to be closer than near objects with small offsets. We predict such systematic errors. Only if observers were able to factor the angle between direction of motion and object into their judgments, that is, use global tau, would they be able to perceive distance in depth veridically. The data from DeLucia and Novak (1997), mentioned earlier, provide preliminary evidence that observers may fail to do so.

In contrast to DeLucia and Novak (1997), Kaiser and Mowafy (1993) provided evidence for observers' ability to use global tau. To distinguish experimentally between local and global tau, they constructed displays that consisted entirely of single-pixel dots. Because the image of the approaching object did not expand, local tau was not available. In Experiment 1 Kaiser and Mowafy found that observers were able to make reliable relative TTP judgments when approached by two objects off axis. Performance was superior when relative motion was added as a second cue for relative depth. Relative motion was present when the two targets were placed on the same side of the direction of motion and the angle between them was either expanding or contracting. However, the authors stated that observers could have used a heuristic that maps contraction to the judgment that the target closer to the direction of motion will pass first and expansion to the judgment that the target with the larger offset will pass first in the relative motion condition. In Experiment 2 they found that absolute TTP judgments were well correlated with actual TTP.

Although Kaiser and Mowafy (1993) and Tresilian (1995) interpreted these results as evidence for observers' sensitivity to global tau, it appears likely that one or more cues unrelated to global tau influenced judgments. One heuristic that could be used in the relative motion condition indicates an overreliance on image velocity. In the case of contraction, the target closer to the direction of motion had a higher image velocity, whereas for expansion it was the target far from the direction of motion. Thus, observers may have judged the target with the highest image velocity to pass first. In conditions in which the targets were placed on opposite sides of the direction of motion, Kaiser and Mowafy reported no effect of lateral target offset. However, this result might have been due to an uncontrolled variable in their experimental design: Across all combinations of target offset and TTP difference, the number of trials in which the target far from the direction of motion was the first to pass was not equal to the number of trials in which the target close to the direction of motion was the first to pass. Kaiser and Mowafy included only distractor trials to equate the number of times the first target to pass was nearer or farther from the direction of motion.

In the following experiments, we tested two predictions derived from the assumption that global tau guides TTP judgments. First, TTP judgments should be independent of the target's distance from the direction of motion. If, on the other hand, observers perceive targets with a high image velocity to be closer to the observation point irrespective of global tau information, performance should be affected by target offset. In Experiments 1–5 we systematically varied offset from the direction of motion, thereby providing conflicting information from global tau and image velocity. Second, given the dependency of global tau on the (implicit) identification of the direction of motion, we expected TTP judgments to be less accurate in conditions in which the perception of the direction of motion was made difficult. In contrast, if judgments are based exclusively on image velocity, a variable that is independent of the direction of motion, they should be unaffected. Therefore, we decoupled direction of motion and direction of gaze in Experiments 3–5 and reduced the number of dots to just two in Experiment 4.

Experiment 1: Relative Judgments

The purpose of Experiment 1 was to evaluate the effects of target offset on TTP judgments. Using the relative judgment task that Kaiser and Mowafy (1993) used, we manipulated target offsets in a fully crossed factorial design. Observers were confronted with a cloud of single-pixel objects and were required to judge which one of two colored targets would pass their eye plane first (see Figure 2). Note that this experiment is a partial replication of Kaiser and Mowafy's (1993) first experiment, except that we did not mix same-side (trials with relative motion) and different-

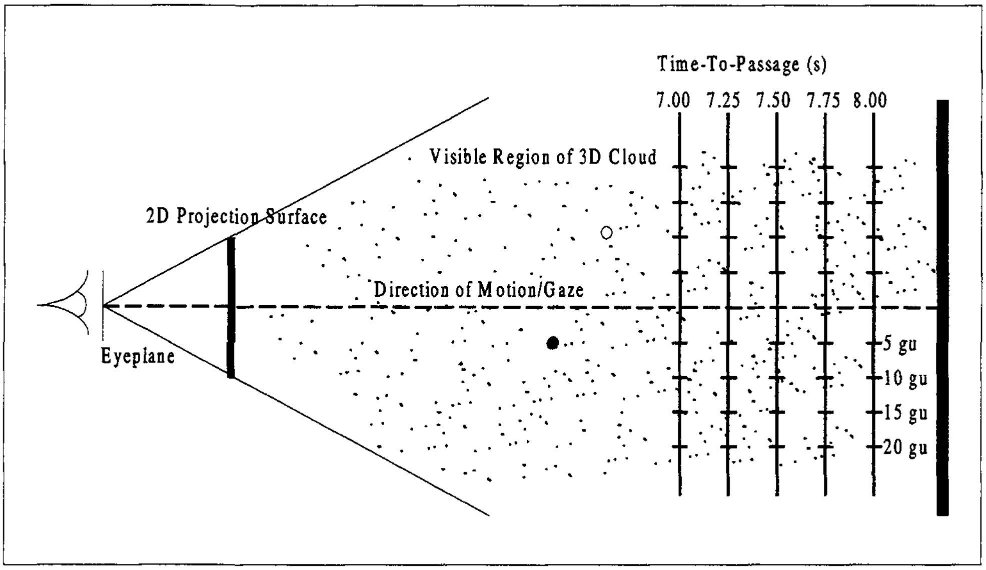

Figure 2. Overhead view of the stimulus space in Experiment 1. The two targets are indicated by the hollow and filled circles, respectively. They were constant-size single-pixel dots of different colors. gu = graphical units.

side conditions. By varying target offset we provided conflicting information from global tau and image velocity. For targets spaced symmetrically around the direction of motion, global tau information and image velocity information corresponded, that is, targets with larger image velocities were closer to the observer than targets with smaller image velocities. For asymmetrically spaced targets, image velocity was valid only when the leading target had a larger offset than the trailing target. When the trailing target was offset by a larger distance from the direction of motion, its image velocity could be higher than the velocity of the leading target. In this case, image velocity and global tau provided conflicting information (i.e., targets with smaller image velocities were closer to the observer than targets with higher image velocities). Image velocities for the different conditions are graphed in Figure 3.

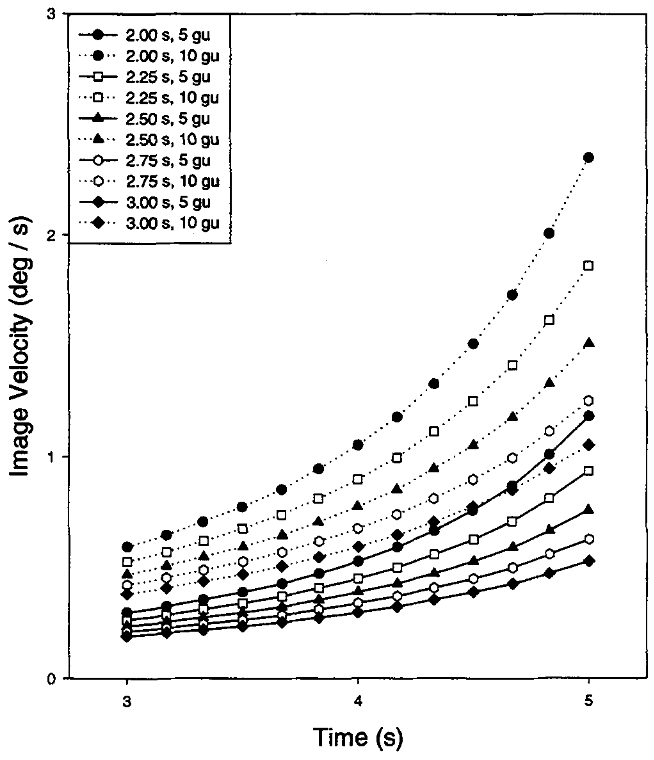

Figure 3. Image velocity (global expansion) of targets offset laterally by 5 and 10 graphical units (gu) for the last 2 s before display termination. The complete animation lasted 5 s. Time-to-passage (TTP) denotes the time remaining until the target passed the observer when the animation stopped. Values range from 2 to 3 s. Note that the image velocity is higher for the leading target (TTP = 2 s) in pairings with equal offsets (symmetric conditions). The same is true if a leading target offset by 10 gu and a trailing target (TTP $>$ 2 s) offset by 5 gu are paired (asymmetric condition). In this case the difference in image velocity is even more pronounced than in the symmetric condition. However, a leading target offset by 5 gu is moving faster than a trailing target offset by 10 gu only at TTP differences as large as 1,000 ms. If observers perceived the target with the highest image velocity to pass by first, 100% correct responses are predicted in the symmetric conditions provided that velocity differences are detected reliably.

Method

Participants. Eight students at the University of Bielefeld were paid for their participation. All participants had normal or corrected-to-normal vision.

Stimuli. The stimuli were created with a Silicon Graphics Personal Indigo2 workstation. The display had a pixel resolution of 1,280 × 1,024 (width × height) pixels on a 48-cm (diagonal) screen with a refresh rate of 60 frames/s. It subtended 42° × 32° (width × height).

Stimulus displays simulated an elongated cloud of 600 white single-pixel dots that extended into depth in front of the observer. Two different-colored target dots were placed in this cloud. The volume was 684 graphical units (gu) deep. One graphical unit in the computer program corresponded to 2.54 cm (1 in.) in virtual space. The observer was translated through the cloud on a linear track at a simulated speed of 1 gu per frame or 1.52 m/s. The leading target was 2 s from passage at display termination. These parameters were the same as in Kaiser and Mowafy's (1993) Experiment 1. Each animated sequence lasted 5 s (300 frames). Dots that went out of sight were not replaced.

Design. A three-factor within-subjects design was used. The TTP difference between the leading and trailing target was manipulated by varying the distance between the two targets and the observer. TTP differences were 250, 500, 750, and 1,000 ms. The second factor was the symmetry of target location with regard to direction of motion ("track vector" in Kaiser and Mowafy's, 1993, terminology). The two targets were offset by 5, 10, 15, or 20 gu on opposite sides of the direction of motion, yielding 16 possible combinations of target locations. In 4 of these combinations, the targets were displaced by the same lateral offsets, creating symmetric configurations. In the other 12 combinations, the distance of the two targets differed, thus creating asymmetric configurations. The third factor was the offset of the leading target. The leading target was offset laterally by 5, 10, 15, or 20 gu. Each combination of the four TTP differences and 16 target locations was duplicated by reversing the leading target, resulting in 128 distinct trial types.

Procedure. Participants sat in a dimly lit room 45 cm from the screen. Their chins were placed in a chin rest; viewing was binocular. Participants were told that they would be watching stimuli simulating their own movement through a 3-D cloud of white dots. Their task was to judge which one of the two colored target dots would have passed them first if the movement had continued. Participants initiated a trial by pressing the space bar on the keyboard. On each trial the first frame of the display was shown for 1 s before the animation started. This was done to ensure that the participants were able to locate the targets. The animation lasted 5 s. The last frame of the display remained visible until the participants pressed one key if they thought that the left target would pass by first or another key if they thought that the right target would pass by first. No feedback was provided, either in the practice or in the experimental trials.

In eight practice trials displays with temporal separation between targets of 1,250 ms and offset of 5 gu for both targets were presented. The total experiment lasted about 30 min.

Results

Figure 4 shows the mean proportions correct. Correct answers received a score of 1 and incorrect answers a score of 0. Performance was significantly above chance, $t(7) = 9.29, p < .0001$. Individual performance ranged from .59 to .75 proportion of correct responses ($m = .70$). A repeated measures analysis of variance (ANOVA) showed that the

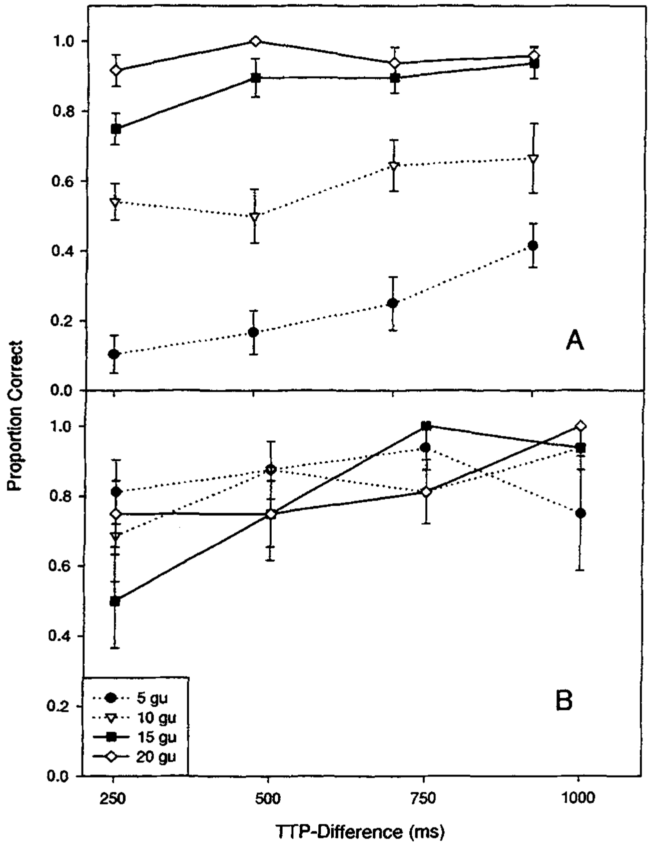

Figure 4. Mean proportions correct and standard errors as a function of time-to-passage (TTP), symmetry, and lateral offset of the leading target in Experiment 1. A: Data from asymmetric target arrangement. B: Data from symmetric target arrangement. Correct answers received a score of 1 and incorrect answers received a score of 0. gu = graphical units.

proportion correct increased with TTP, $F(3, 21) = 10.43$, $p < .0002$. Performance was better with symmetric target arrangement, $F(1, 7) = 18.04$, $p < .0038$, and with large lateral offset of the leading target, $F(3, 21) = 66.06$, $p < .0001$. The interaction between symmetry and offset of the leading target, $F(3, 21) = 43.07$, $p < .0001$, reached significance. To assess the effect of distance of the leading target from the direction of motion, we conducted separate ANOVAs on the data from the symmetric and asymmetric conditions. In the asymmetric conditions, performance increased with the leading target's offset from the direction of motion, $F(3, 21) = 83.26$, $p < .0001$, but not in the symmetric conditions. Furthermore, the interactions among TTP difference, symmetry, and offset of the leading target, $F(9, 63) = 2.23$, $p < .0311$, was significant.

Regressions of the angular separation of the targets at display termination on correctness scores were run for each observer individually. One of eight regression coefficients was negative; the remainder were positive. The mean variance explained was 1.6%. Thus, difficulties in scanning could be ruled out because the amount of variance explained was small and the sign of the coefficient was mostly positive, indicating better performance with large angular separation.

To assess the role of the image velocity of the leading and trailing target, we ran regressions of the final image velocity (computed between the last two frames) on correctness scores for each observer. Regression coefficients (not standardized) ranged from .11 to .18 for the image velocity of the leading target, from −.26 to −.12 for the trailing target, and from .12 to .20 for the relative image velocity (i.e., the difference between the image velocities of the leading and trailing targets). The mean variance explained was 21.1% for the image velocity of the leading target, 16.4% for the trailing target, and 36.5% for the relative image velocity. We also calculated the average image velocities of the targets during the animated sequence and regressed these values on correctness scores. Because final and average image velocities are highly correlated, an almost identical amount of variance was explained. The variance explained was 21.1%, 16.0%, and 36.5% for the image velocities of the leading and trailing target and the difference between the two, respectively. Unsigned regression coefficients were larger than those computed for the final image velocity. This reflects the fact that image velocity increased nonlinearly from the first to the last frame so that the average was smaller than the final velocity. Regression coefficients ranged from .38 to .65 for the image velocity of the leading target, from −.40 to −.79 for the trailing target, and from .42 to .67 for the relative image velocity.

Discussion

The results suggest that the optic flow patterns provide enough information to make reliable TTP judgments. Performance was better with larger temporal separations of the targets and symmetric configuration of the targets. The overall performance was comparable to the performance in Experiment 1 of Kaiser and Mowafy (1993), ranging from .61 proportion of correct responses with a 250-ms temporal separation to .79 with a 1,000-ms separation of leading and trailing target. Performance in the tau-only condition in Kaiser and Mowafy's Experiment 1 was approximately .55 proportion of correct responses with a 250-ms separation and .80 with a 1,000-ms separation. Performance was better when the targets were symmetrically spaced around the direction of motion. In the asymmetrical conditions, targets that were offset farther from the direction of motion were judged to pass by first. Regressions showed that observers relied heavily on image velocity (i.e., they perceived the fastest moving target as passing by first). Because image velocity is only a partially valid cue to distance in depth, poor performance resulted when the leading target was close to the direction of motion and hence its image velocity was relatively small.

Image velocity seemed to explain the data better than did global tau. For symmetrically spaced targets, image velocity and global tau both accounted for the performance in these cases. However, for asymmetric trials, only the relative image velocity of the two targets reflected actual performance. Decisions based on the highest image velocity (computed for the last two frames) led to an expected .08 proportion correct for 5-gu offset, .67 for 10-gu offset, .91 for 15-gu offset, and 1.00 proportion correct for 20-gu offset. The actual mean proportions correct were .39, .65, .85, and .92, respectively. On symmetric trials, the leading target always had a higher image velocity. However, performance in these conditions fell short of the perfect performance predicted by exclusive reliance on image velocity. Possibly, the smaller differences in angular velocities between leading and trailing target in the symmetric conditions were more difficult to detect than the large difference between leading and trailing target in the asymmetric condition with a leading target offset by a large distance (see Figure 3). Thus, in the present experimental setup, observers did not exploit global tau information when judging relative TTP. Rather, they seemed to base their judgments on image velocity (i.e., they perceived fast moving objects to be closer to the point of observation than slowly moving objects).

These results are not consistent with the findings of Kaiser and Mowafy (1993), who reported no effect of the position of the leading target. The only appreciable difference with respect to their first experiment was that they did not include position of the leading target as a factor.

In summary, Experiment 1 showed that observers' relative TTP judgments were largely determined by the image velocities of the targets. Observers tended to judge an object point that had a higher image velocity to be nearer, irrespective of the angle between object point and direction of motion. Thus, image velocity seemed to override global tau information.

Experiment 2: Absolute Judgments

The effects of image velocity on relative TTP judgments might not generalize to absolute judgments, however. As hypothesized by Tresilian (1995), relative judgment tasks might be particularly prone to the use of response strategies. Absolute judgments, on the other hand, are more likely to reflect observers' perception of arrival time. Kaiser and Mowafy (1993) reported in their Experiment 2 that absolute judgments were well correlated with actual TTP. However, regressions of the position of the leading target onto absolute judgments were not reported, leaving open whether image velocity would be able to explain absolute TTP judgments. Moreover, in Kaiser and Mowafy's experimental procedure, targets were visible until they exited the field of view (FOV) at ±23°. Observers were required to indicate when a target would pass by them if it were to continue its approach. Consequently, offset correlated positively with TTP: Targets with large offsets left the FOV at a larger distance from the observer, resulting in higher TTPs at exit. Looking at the global tau formula, it is evident that if the angle subtended between the object and direction of motion remained constant (23° in all cases), the rate of change of that angle would have to be different if TTP is to vary. Thus, for small TTPs (and small offsets), image velocity was high at exit from the FOV, and for large TTPs (and large offsets), the image velocity was lower. Thus, image velocity was a 100% valid cue in Kaiser and Mowafy's Experiment 2. To partially eliminate the validity of the image velocity induced by Kaiser and Mowafy's experimental procedure, offset (and thereby final eccentricity) and TTP would have to be decorrelated. The rectangular stimulus space of Experiment 1, in which targets at varying offsets stopped moving at a particular TTP from the observer, served this purpose. Thus, the goal of the second experiment was to remove the artificial validity of the image velocity cue and to examine the effects of offset on absolute TTP judgments in conditions that closely resembled those of Experiment 1.

Method

Participants. Eight students at the Ludwig-Maximilians-University of Munich were paid for their participation. All participants had normal or corrected-to-normal vision.

Stimuli. The same viewing geometry and simulated movements were used as in Experiment 1 with the following exceptions: Stimuli were generated by a Matrox Mystique graphics card that was hosted by a Pentium 166 computer. Only one colored target dot was visible for 5 s. Observers pressed a mouse button to indicate when the target would pass by them.

Design. A two-factor within-subjects design was used. TTP was manipulated by varying the distance between the target and the observer. TTPs were 1,500, 1,750, 2,000, 2,250, 2,500, 2,750, and 3,000 ms when the target dot disappeared. The second factor was the target location with regard to the direction of motion. The target was offset by 5, 10, 15, or 20 gu from the direction of motion. The seven TTP differences and four target locations were fully crossed, duplicated by reversal about the direction of motion and presented three times in random order (168 cases).

Procedure. The procedure was the same as in Experiment 1 with the following exceptions: Binocular cues to the screen surface were removed by making viewing monocular. We were therefore able to rule out accommodation and stereo cues that might interfere with the impression of motion in depth (Koenderink, van Doorn, & Kappers, 1994). One target dot appeared to the left or the right of the direction of motion, and observers were instructed to imagine the target continuing its approach after it had disappeared and to press the mouse button when they thought it would pass by them. The dots in the flow field continued to move until the observer pressed the mouse button. Observers received eight practice trials randomly drawn from the 56 possible conditions. No feedback was provided, either in the practice or in the experimental trials. Trials in which observers responded more than 3 s after the actual TTP were repeated in the remainder of the experiment. These trials accounted for 1.3% of all trials.

Results

Figures 5, 6, and 7 show mean judged TTP, mean absolute, and constant error. Absolute errors were the unsigned deviations of judged TTP from actual TTP, whereas constant errors were the signed deviations. An ANOVA on judged TTP revealed a significant effect of TTP, $F(6, 42) = 29.46, p < .0001$, and offset, $F(3, 21) = 28.81, p < .0001$. Judged TTP increased with actual TTP. When the target was offset by a large distance from the direction of motion, judged TTP was shorter. A main effect of TTP on constant error was observed, $F(6, 42) = 17.27, p < .0001$. Observers tended to overestimate short TTPs and underestimate large TTPs. Most importantly, TTP was overestimated when the

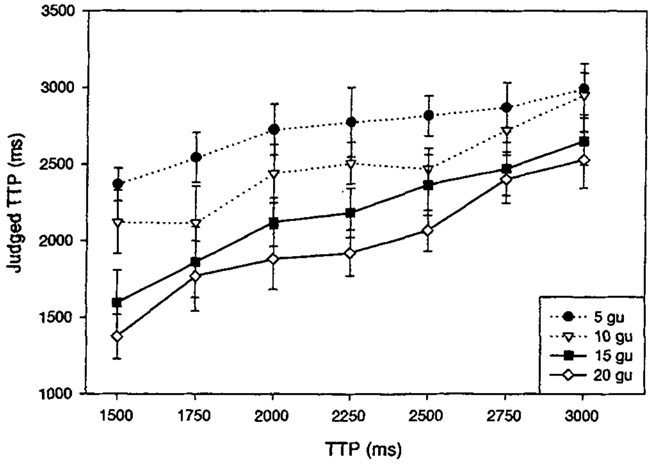

Figure 5. Mean judged time-to-passage (TTP) and standard errors as a function of TTP and lateral target offset in Experiment 2. gu = graphical units.

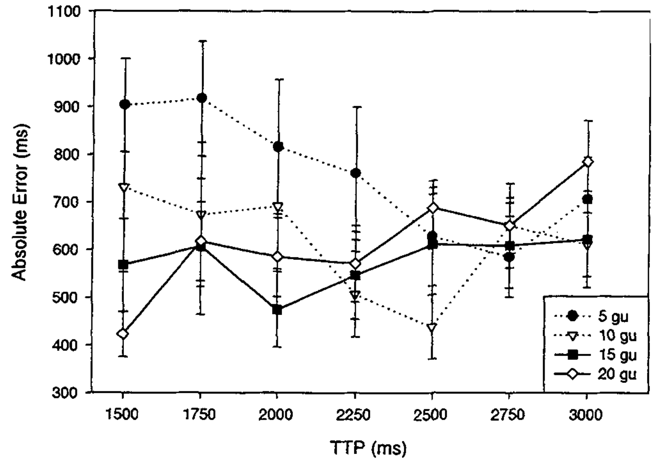

Figure 7. Mean absolute and standard errors as a function of time-to-passage (TPP) and lateral target offset in Experiment 2. gu = graphical units.

target was close to the direction of motion but underestimated when offsets were large, $F(3, 21) = 28.81, p < .0001$. An ANOVA showed no main effects on absolute error but a significant interaction between TTP and offset, $F(18, 126) = 2.35$, $p < .0031$, which was due to larger absolute errors with small offset and small TTPs.

Regressions of actual TTP on judged TTP for each observer resulted in individual regression coefficients (not standardized) between .32 and .88 and exclusively positive intercepts. The mean variance explained was 15.9% (range = 4.4%–28.3%). That regression coefficients were all smaller than one and intercepts were all positive indicated temporal compression. Regressions of final image velocity on judged TTP for each observer explained 8.2%–57.2% of the variance ($M = 30.8\%$). The regression coefficients ranged from −347.34 to −134.27 and had positive intercepts. As in Experiment 1, regressing the average image velocity on judged TTP yielded an almost identical amount of explained variance and larger unsigned regression coefficients. The mean variance explained was 30.8%, and the regression coefficients ranged from −641.74 to −1,444.01.

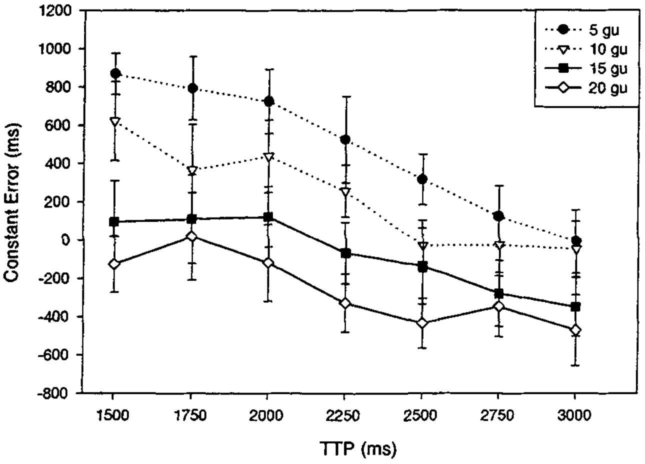

Figure 6. Mean constant and standard errors as a function of time-to-passage (TTP) and lateral target offset in Experiment 2. gu = graphical units.

Discussion

The effect of actual TTP on judged TTP showed that observers were able to do the task. Judged TTP increased linearly with actual TTP. As in Kaiser and Mowafy's (1993) Experiment 2, shorter TTPs were overestimated and longer TTPs were underestimated. However, judged TTP was not as well correlated with actual TTP as it was in Kaiser and Mowafy's experiment. They reported that actual TTP explained between 55% and 84% of the variance of TTP judgments ($M = 73\%$). This difference might have been attributable to the FOV exit procedure used in their experiments, in which image velocity was a 100% valid cue, but other explanations cannot be ruled out. The greater compelling nature of Kaiser and Mowafy's large-screen display and the larger range of TTPs (1–3 s) might have enhanced performance. However, Kaiser and Mowafy reported no effect of display size (Experiments 1a and 1b), rendering the first alternative unlikely. Consistent with the findings obtained in the relative judgment task of Experiment 1, we found a strong influence of the offset of the target from the direction of motion. TTP was overestimated when the target was close to the direction of motion and underestimated when it was far. This result favors image velocity rather than global tau as depth information.

Experiment 3:
Decoupling Movement Direction and Gaze Direction

Experiments 1 and 2 showed that both relative and absolute TTP judgments were strongly affected by lateral target offset, which indicates that observers relied on image velocity when judging TTP. To further test this claim, we manipulated gaze-movement angle (i.e., the angle between direction of motion and direction of gaze), a variable that should affect TTP judgments if observers used global tau but not image velocity. Decoupling the direction of motion and the direction of gaze (see Figure 8) has been referred to as the "fixed camera angle technique" (Cutting, 1986) and "crab angle" (Kaiser & Hecht, 1995). In contrast to simulated eye rotation (e.g., Warren & Hannon, 1990), the angle between direction of motion and direction of gaze does not change continuously but remains fixed.

Kaiser and Hecht (1995) investigated how observers' global TTP judgments were affected by the presence of acceleration and simulated observer rotation. In their first experiment they showed that observers did not use acceleration information. Their second experiment demonstrated that head rotation about the *z*-axis did not affect TTP judgments. However, when the direction of motion and gaze direction were decoupled by more than 10° in a third experiment, poor performance resulted. This effect of gaze-movement angle is consistent with findings by Crowell and Banks (1993) that judgments of direction of motion become less accurate with larger gaze-movement angles. The purpose of our third experiment was thus to evaluate the effects of target offset and gaze-movement angle on relative TTP judgments. Using the same relative TTP judgment task as in Experiment 1, we manipulated both gaze-movement angle and target offset.

Method

Participants. Ten undergraduate students at the University of Connecticut participated in partial fulfillment of a course requirement. All participants had normal or corrected-to-normal vision.

Stimuli and procedure. The displays were created on an SGI computer identical to the one used Experiment 1. Viewing geometry and simulated movements were the same with the following exceptions: Observers viewed the displays from a distance of 50 cm. The viewing geometry was changed accordingly. As in Experiment 1, viewing was binocular and a relative arrival-time judgment had to be made on each trial. To make our procedure more similar to that of Kaiser and Hecht's (1995) Experiment 3, we provided feedback in both experimental and practice trials. Given that there is no consensus on the benefits of providing feedback (see Tresilian, 1995, for arguments in favor; DeLucia & Novak, 1997, for arguments against; and Kaiser & Mowafy, 1993, for a no-difference finding), we tested whether the results of Experiments 1 and 2 would be stable across feedback manipulations.

Design. A four-factor within-subjects design was used. There were three levels of the gaze-movement angle factor. Gaze direction was deflected by 5°, 10°, and 15° from the direction of motion. Thus, both target dots were displaced to the right or to the left of the center of the screen. The TTP difference between the two targets was manipulated by varying the distance between the two targets and the observer, and TTP differences were 250, 500, 750, and 1,000 ms. The first target would pass the observer 2 s after the display stopped moving. The third factor was the symmetry of target location with regard to the direction of motion. The two targets were offset by 5 or 10 gu to opposite sides of the direction of motion, yielding four possible combinations of target locations. In two of these combinations, the targets were displaced by the same distance, thus creating a symmetric configuration. In the other two combinations, the distance of the two targets differed, thus creating an asymmetric configuration. The fourth factor was the offset of the leading target. The leading target was offset by 5, 10, 15, or 20 gu. The three gaze-movement angles, four TTP differences, and four target locations were fully crossed and duplicated by reversing the leading target. In addition, all trials were reflected about the direction of motion, once with the gaze directed to the left and once to the right of the direction of motion (192 cases).

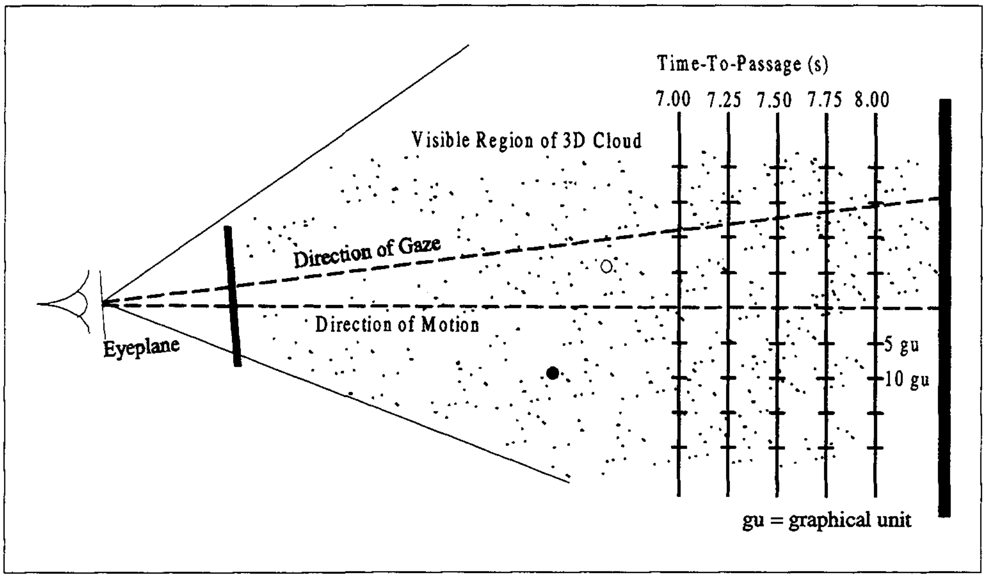

Figure 8. Overhead view of the stimulus space and viewing geometry in Experiment 3. Direction of motion and direction of gaze are decoupled, resulting in gaze-movement angles larger than zero.

Results

Figure 9 shows the mean proportions of correct responses for each within-subjects effect. Correct answers received a score of 1 and incorrect answers a score of 0. Overall performance was significantly above chance, $t(9) = 11.26$, $p < .0001$. Individual performances ranged from .58 to .79 proportion of correct responses ($M = .72$). A repeated measures ANOVA showed that performance increased with TTP difference, $F(3, 27) = 18.26, p < .0001$. The proportion of correct responses was higher with symmetric target arrangement, $F(1, 9) = 29.88, p < .0004$, and large offset of the leading target, $F(1, 9) = 50.12$, $p < .0001$. The interaction between symmetry and position of the leading target, $F(1, 9) = 89.24, p < .0001$, reached significance. To assess the effect of distance of the leading target from the direction of motion, we conducted separate ANOVAs for the symmetric and asymmetric configurations. A significant effect on performance emerged in the asymmetric condition, $F(1, 9) = 95.37$, $p < .0001$, but not in the symmetric conditions. Judgments in the asymmetric condition were less accurate when the leading target was close to the direction of motion than when it was far. Furthermore, the interaction between TTP difference and position of the leading target, $F(3, 27) = 3.47, p < .0297$, reached significance, indicating that performance increased more with TTP difference in conditions with small offset of the leading target. A three-way interaction among TTP difference, symmetry, and position of the leading target, $F(3, 27) = 4.48, p < .0112$, indicated that the effect of TTP difference was uniform with symmetric target spacing for both offset conditions but that it was not with asymmetric target spacing. No effect of gaze-movement angle was found.

Furthermore, the angular separation of the targets at display termination was regressed on correctness scores for each observer. Five of 10 regression coefficients were negative, and the remaining coefficients were positive. A mean of 0.7% of the variance was accounted for. Given the small amount of variance explained, difficulties in scanning could be ruled out.

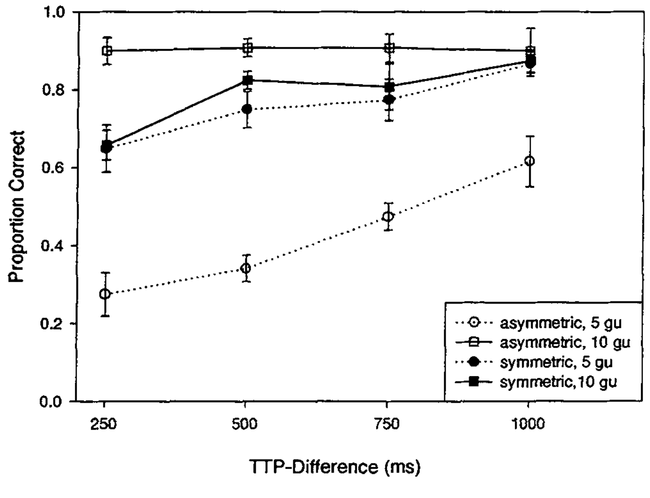

Figure 9. Mean proportions correct and standard errors as a function of time-to-passage (TTP), symmetry, and lateral offset of the leading target in Experiment 3. Correct answers received a score of 1 and incorrect answers, a score of 0. gu = graphical units.

Discussion

The results suggest that the observers were able to make reliable relative TTP judgments even in the presence of gaze-movement angles larger than 0°. Performance was better with larger temporal separation of the targets and symmetric configuration of the targets. The overall performance was comparable to the observers' performance in Kaiser and Mowafy's (1993) Experiment 1, ranging from .62 correct responses with a 250-ms temporal separation to .81 with a 1,000-ms separation of leading and trailing target. Although the use of global tau depends on the correct identification of gaze and motion direction, gaze-movement angle did not affect performance. Thus, we failed to replicate the effect of gaze-movement angle on absolute error reported by Kaiser and Hecht (1995). The discrepancy might have been due to the different dependent variables (absolute vs. relative judgments) and a smaller range of offsets in the present experiment.

The poor performance in the asymmetric conditions suggested that observers again perceived the fastest moving object as likely to pass by first. This cue was valid when the leading target was offset by a larger distance from the direction of motion or when the two targets were offset by the same distance, but misleading if the leading target was offset by a smaller distance (see Figure 3). Reliance on image velocity is consistent with the absence of an effect of gaze-movement angle and inconsistent with the global tau hypothesis.

The results of the previous experiments suggest that observers base their judgments of TTP on image velocity. This strategy does not require an analysis of the global flow field. In contrast, Tresilian (1991) conceptualized global tau as a variable that refers to a feature of the global flow field, the FOE as a specification of the direction of motion. Tresilian (1995) argued that uncertainty in estimating global tau arises from uncertainty in estimating the FOE. To support this claim, he calculated TTP difference thresholds assuming that heading thresholds largely determine TTP thresholds. When predicting TTP thresholds for the stimuli of Kaiser and Mowafy (1993) using heading thresholds determined by Warren et al. (1988), he found a close fit to the data of Kaiser and Mowafy's (1993) Experiment 1. Predicted and actual TTP thresholds (the interpolated 75% correct data point) ranged from 500 to 750 ms.

We applied Tresilian's (1995) threshold analysis to the present data. Given that Tresilian did not reverse the position of the leading target for asymmetric offset combinations, we calculated the predicted TTP thresholds for the conditions of Experiment 1. According to Tresilian (1993, 1995) the TTP difference thresholds, Θ_T, between two targets is given by

$$\Theta_T = 0.5 * (Z_1 * Z_1 * \tan \epsilon_0/R_1 V_1 + Z_2 * Z_2 * \tan \epsilon_0/R_2 V_2),$$

where ϵ_0 is the heading threshold, R denotes the distance from the direction of motion, V is the velocity, and Z is the distance from the observer. In all our experiments V was 1.524 m/s for both targets; R could take values of 0.125, 0.254, 0.381, and 0.508 m; and Z could take values of 3.08 m for the leading target and values of 3.461, 3.842, 4.223, and 4.604 m for the trailing target at display termination.

As shown in Table 1, the mean predicted TTP difference thresholds were 0.6, 0.68, 0.76, and 0.86 s for the temporal difference in TTP of 250, 500, 750, and 1,000 ms, respectively, implying that the 75% correct threshold in Experiment 1 should have been less than 1.0 s and greater than 0.5 s. This was clearly the case. The mean proportions correct were .61, .68, .73, and .79 for TTP differences of 250, 500, 750, and 1,000 ms. Note, however, that the pattern of predicted thresholds deviated in two important aspects from the results of Experiment 1. First, predicted thresholds were lower in symmetric conditions with large offsets. In Experiment 1 no effect of the offset of the leading target was obtained. If there was a trend at all, it was in the opposite direction. Second, predicted thresholds were lower for asymmetric offset conditions in which the leading target was closer to the direction of motion than the trailing target, whereas they were higher when the leading target was farther than the trailing target. This pattern is inconsistent with findings from Experiments 1 and 3.

Thus, a model of TTP judgments that incorporated FOE thresholds failed to explain the obtained effects. Our simpler assumption stating that observers relied on image velocity fit the data much better. If observers did indeed rely more on image velocity than on global flow, an extreme prediction can be made: Reducing the number of dots to just two should still result in above-chance performance.

Table 1
Estimated TTPD Thresholds for the 64 Conditions in Experiment 1

Target distance from direction of motion (m)		TTPD-thresholds (s)				
R_1	R_2	250-ms TTPD	500-ms TTPD	750-ms TTPD	1,000-ms TTPD	*M*
0.125	0.125	1.16	1.31	1.48	1.66	1.40
0.125	0.254	0.90	1.05	1.22	1.40	1.14
0.125	0.381	0.81	0.97	1.13	1.32	1.06
0.125	0.508	0.77	0.92	1.09	1.27	1.02
0.254	0.125	0.83	0.90	0.99	1.08	0.95
0.254	0.254	0.57	0.64	0.73	0.82	0.69
0.254	0.381	0.49	0.56	0.64	0.73	0.61
0.254	0.508	0.44	0.52	0.60	0.69	0.56
0.381	0.125	0.72	0.77	0.83	0.89	0.80
0.381	0.254	0.46	0.51	0.57	0.63	0.54
0.381	0.381	0.38	0.43	0.48	0.54	0.46
0.381	0.508	0.34	0.39	0.44	0.50	0.42
0.508	0.125	0.67	0.71	0.75	0.79	0.73
0.508	0.254	0.41	0.45	0.49	0.53	0.47
0.508	0.381	0.33	0.36	0.41	0.45	0.39
0.508	0.508	0.28	0.32	0.36	0.41	0.34
M		0.60	0.68	0.76	0.86	

Note. R_1 and R_2 denote the distances of two targets from the direction of motion. The heading threshold was assumed to be 1.2°. The target offset by R_2 was leading. Its final distance from the observer was 3.08 m. The target offset by R_1 was at a distance of 3.461, 3.842, 4.223, and 4.604 m at display termination, yielding differences in time-to-passage (TTPD) of 250 to 1,000 ms.

Table 2
Estimated TTPD Thresholds for the 16 Conditions in Experiment 3

Target distance from direction of motion (m)		TTPD thresholds (s)				
R_1	R_2	250-ms TTPD	500-ms TTPD	750-ms TTPD	1,000-ms TTPD	*M*
0.125	0.125	1.16	1.31	1.48	1.66	1.401
0.125	0.254	0.90	1.05	1.22	1.40	1.141
0.254	0.125	0.83	0.90	0.99	1.08	0.949
0.254	0.254	0.57	0.64	0.73	0.82	0.689
M		0.86	0.98	1.10	1.24	

Note. R_1 and R_2 denote the distances of two targets from the direction of motion. The heading threshold was assumed to be 1.2°. The target offset by R_2 was leading. Its final distance from the observer was 3.08 m. The target offset by R_1 was at a distance of 3.461, 3.842, 4.223, and 4.604 m at display termination, yielding differences in time-to-passage (TTPD) of 250 to 1,000 ms.

Experiment 4: Two Dots

To test the above prediction, we presented observers with displays that consisted only of the two targets. Warren et al. (1988) confirmed that estimation of the direction of motion was still possible but degraded when global flow-field information was absent in displays with only two dots. Thresholds for the detection of the direction of egomotion (heading thresholds) rose to 2.5° in conditions in which only two dots were presented and dropped to 1.2° in dense flow fields. Following the analysis of Tresilian (1995), thresholds for TTP discrimination should rise when heading thresholds are elevated. Tables 2 and 3 show the predicted TTP thresholds for heading thresholds of 1.2° and 2.5° and the

Table 3
Estimated TTPD Thresholds for the 16 Conditions in Experiment 4

Target distance from direction of motion (m)		TTPD thresholds (s)				
R_1	R_2	250-ms TTPD	500-ms TTPD	750-ms TTPD	1,000-ms TTPD	*M*
0.125	0.125	2.41	2.73	3.08	3.46	2.919
0.125	0.254	1.87	2.19	2.54	2.92	2.379
0.254	0.125	1.73	1.88	2.06	2.24	1.977
0.254	0.254	1.19	1.34	1.51	1.70	1.437
M		1.80	2.04	2.30	2.58	

Note. R_1 and R_2 denote the distances of two targets from the direction of motion. The heading threshold was assumed to be 2.5°. The target offset by R_2 was leading. Its final distance from the observer was 3.08 m. The target offset by R_1 was at a distance of 3.461, 3.842, 4.223, and 4.604 m at display termination, yielding differences in time-to-passage (TTPD) of 250 to 1,000 ms.

range of offsets used in Experiment 3. The mean predicted TTP difference thresholds for Experiment 3 were 0.86, 0.98, 1.10, and 1.24 s for the four TTP differences, implying a 75% correct threshold larger than 0.75 s, which was the case. The mean proportions correct for TTP difference of 250, 500, 750, and 1,000 ms were .62, .71, .74, and .81, respectively. In the two-dot condition, the TTP threshold should thus be in the range of 1.8 and 2.58 s, implying a 75% correct threshold far larger than 1 s. We expected a sharp decline in performance if observers rely on global tau. On the other hand, if observers do not make use of the information about their simulated direction of motion but rely instead on image velocity, performance should not deteriorate even if global flow information is completely stripped from the displays.

Method

Participants. Nine undergraduate students at the University of Connecticut participated in partial fulfillment of a course requirement. All participants had normal or corrected-to-normal vision.

Stimuli. The same apparatus, viewing geometry, and simulated movements used in Experiment 3 were used here. The white single-pixel cloud was deleted.

Design and procedure. These were the same as those used in Experiment 3.

Results

Figure 10 shows the mean proportions correct for each within-subjects effect. The results were essentially the same as in Experiment 3. Overall performance was significantly above chance, $t(8) = 12.89$, $p < .0001$. Individual performances ranged from .61 to .77 proportion of correct responses ($M = .70$). Performance increased with TTP difference, $F(3, 24) = 12.32$, $p < .0001$, and symmetry, $F(1, 8) = 58.18$, $p < .0001$. Accuracy was higher with leading targets positioned far from the direction of motion, $F(1, 8) = 78.95$, $p < .0001$. The interaction between symmetry and offset of the leading target reached significance, $F(1, 8) = 140.8$, $p < .0001$. Separate ANOVAs showed that the effect of the position of the leading target was significant in the asymmetric condition, $F(1, 8) = 127.15$, $p < .0001$, but not in the symmetric condition. In the asymmetric condition, performance was better when the leading target was far from the direction of motion than when it was close. An interaction between TTP difference and offset of the leading target emerged $F(3, 24) = 4.06$, $p < .018$, indicating that performance was less affected by TTP difference with large offsets. Also, performance increased more with TTP difference in the symmetric conditions, resulting in an interaction between TTP difference and symmetry, $F(3, 24) = 3.55$, $p < .029$. Again, the effect of gaze-movement angle was not significant. A mixed-factor ANOVA with experiment as a between-subjects factor on the combined data from Experiments 3 and 4 revealed no significant differences between the two experiments. Regressions of the angular separation of the targets at display termination on correctness scores for each observer explained 0.47% of the variance. Two of nine regression coefficients were negative, and the remaining ones were positive.

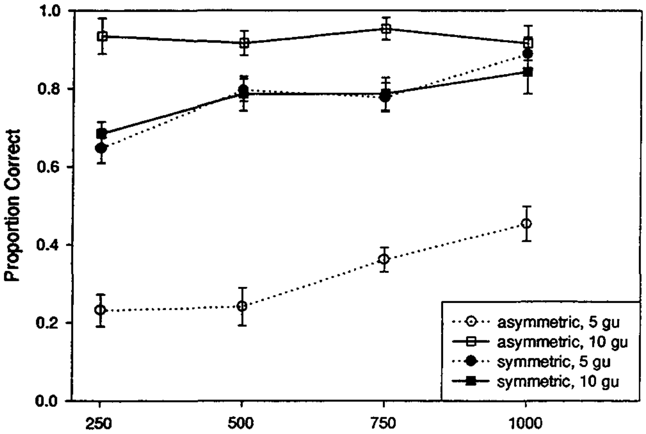

Figure 10. Mean proportions correct and standard errors as a function of time-to-passage (TTP), symmetry, and lateral offset of the leading target in Experiment 4. Correct answers received a score of 1 and incorrect answers a score of 0. gu = graphical units.

Discussion

Surprisingly, observers were able to make TTP judgments above chance in displays at gaze-movement angles ranging from 5° to 15°. Despite the absence of a global flow field, the level of performance was the same as in Experiment 3. Thus, it appears that local image velocities were sufficient to judge TTP with the same degree of accuracy compared with cases in which information about the direction of motion was provided. As in Experiment 3, performance was a function of temporal separation and position of the leading target. Observers again appeared to map larger relative image velocity of a target onto the judgment that the target will pass by first. As a matter of fact, there was no other information on which they could base their judgments. The decline in performance predicted by an analysis in terms of heading thresholds was not observed. Although predicted TTP difference thresholds were larger than in Experiment 3, performance did not differ. This is a strong indication that observers used image velocity cues in both cases.

Experiment 5: Relative Motion

The results from Experiments 1–4 provide strong evidence for the view that observers' relative and absolute TTP judgments are based on image velocity, which leads to a drop in performance if velocity information and actual TTP are in conflict. However, one concern remains. Kaiser and Mowafy (1993) found that TTP judgments were more accurate when observers used a heuristic that mapped contraction of the angular separation between the targets placed on the same side of the direction of motion to the judgment that the target nearer to the direction of motion will pass by first. Expansion, on the other hand, was mapped onto the judgment that the target nearer the direction of motion will pass by second. Note that this heuristic is identical to the strategy of using image velocity as a basis for TTP judgments. If the image distance between the targets is contracting, then the target nearer the direction of motion has a higher image velocity. In the case of expansion, the target far from the direction of motion moves faster. This cue is valid only if the targets are symmetrically spaced around the direction of motion or if the leading target is far from the direction of motion and the trailing target is close. Thus, it is somewhat surprising that Kaiser and Mowafy found superior performance in the relative motion condition given that the expansion–contraction cue is only partially valid. A replication attempt was made to assess the strategies that might be used for same side targets. Only asymmetric target offsets from the direction of motion were used for this purpose.

Method

Participants. Eight undergraduate students at the University of Connecticut participated in partial fulfillment of a course requirement. All participants had normal or corrected-to-normal vision.

Stimuli. The same apparatus, viewing geometry, and stimuli used in Experiment 3 were used here, with one exception. To ensure that the targets were on screen at display termination even in conditions with large offsets from the direction of motion and maximum gaze-movement angle, we changed the animation to be appropriate for a viewing distance of 45 cm.

Design and procedure. The design was the same as in Experiment 3 except that the location of the targets was changed. In each trial, target offsets of 5 and 10 gu from the direction of motion were presented so that the symmetric configurations of Experiment 1 were eliminated. The targets appeared either on the same side of the direction of motion or on opposite sides of the direction of motion, thus always creating asymmetric configurations. The same values of decoupling between direction of motion and gaze angle (5°, 10°, and 15°) were used. The same procedure was used as in Experiment 3, except that the viewing distance was changed to 45 cm.

Results

Overall performance was significantly above chance, $t(7) = 3.62$, $p < .0085$. However, the effect was small. Individual performances ranged from .49 to .63 correct responses ($M = .55$). A three-way within-subjects ANOVA revealed a significant main effect of position of the leading target, $F(1, 7) = 20.26$, $p < .0028$. Responses were more accurate when the leading target was far from the direction of motion ($M = .81$, $SE = .07$) than when it was near ($M = .31$, $SE = .05$). No other effects reached significance.

Discussion

The results show that relative TTP judgments were not influenced by the presence of the relative motion cue. Position of the leading target had a significant effect on performance regardless of whether the targets were placed on the same or on different sides of the direction of motion. As in the previous experiments, this result indicates observers' tendency to select the target with the higher image velocity. Performance did not improve with the relative motion cue. This finding is not consistent with the results obtained by Kaiser and Mowafy (1993), possibly because of the larger range of offsets and a different design used in their experiments. The results reveal that observers consistently assumed symmetric target arrangement.

General Discussion

According to the concept of global tau, TTP information about an approaching extensionless target is fully specified when the angular position of the target with respect to the observer's direction of motion is given and the change of this angle is picked up. In the present series of experiments, alternative, simpler variables were examined that might be used instead of global tau. We obtained converging evidence that whenever different predictions were made by global tau and image velocity, only the latter could account for performance. Thus, observers appeared to use image velocity, a variable that does not require the identification of the direction of motion as a cue for arrival-time judgments. Two strategies were used to separate global tau from image velocity, which was necessary because they both yield accurate results in most situations of sagittal approach. First, a conflict was established between image velocity and tau by varying the targets' offset from the direction of motion. Whenever targets were placed asymmetrically around the direction of motion, performance dropped markedly because targets that were laterally close to the direction of motion were judged to be farther away than targets that were close to the direction of motion. A second strategy consisted of reducing global tau information while image velocity remained informative. For instance, the direction of motion was made hard to detect by deflecting the direction of gaze from the direction of egomotion. We found that, within limits, observers were still able to make TTP judgments. This was the case even when the displays were entirely stripped from global flow information. Thus, observers did not make use of global tau information.

The error patterns obtained with both strategies can be accounted for by observers' reliance on the image velocities of the targets as a cue to TTP judgments. Irrespective of the angle subtended between the direction of motion and the target, a target with a higher image velocity was likely to be judged to pass by first. Our interpretation of the error pattern is further corroborated by the unchanged performance of observers when the global flow field was removed entirely. These findings are at odds with those of Kaiser and Mowafy (1993), who observed no effect of the position of the leading target. However, the findings are consistent with observers' reliance on simpler optical variables in many TTP and TTC situations, such as absolute size (DeLucia, 1991; DeLucia & Warren, 1994) and relative distance (Law et al., 1993). Our results are not in conflict with Todd's (1981) findings, whose observers exploited local tau and were not misled by image expansion. His displays contained local tau information, whereas our displays contained only global tau information.

Taken together, the results leave little doubt that observers relied on image velocity as a source of depth information as suggested by DeLucia and Novak (1997). Our results are also consistent with ongoing research conducted in the laboratory of John Flach (personal communication, July 21, 1998), who found strong evidence that observers are responding to critical expansion rates, not to critical tau values.

Given the clarity of these results, we now discuss their significance for a theory of global tau. In particular, we list arguments that appear to salvage the concept of tau for global flow approach scenarios and then refute them.

Did the Displays Represent Fair Situations in Which Global Tau Information Could Have Been Exploited?

A number of concerns could be put forth. First, in light of observers' failure to use global tau, the question arises as to whether our simulations were appropriate for testing use of global tau. First, one might argue that observers were unable to detect the direction of motion in our displays and therefore had to resort to a simpler variable. In other words, the displays could have been too artificial or diminished to allow observers to extract their simulated heading direction, which is indispensable for the use of tau. This seems unlikely because we used a setup highly similar to that of Kaiser and Mowafy (1993). Also, Warren et al. (1988) found heading thresholds to be in the range of 1° for similar displays, which should have been more than sufficient for all of our relative proximity judgments. Moreover, in the experiments of Warren et al., the direction of motion and the direction of gaze were always decoupled, resulting in varying FOE locations on the screen. In Experiments 1 and 2, however, we did not vary gaze-movement angle, so the center of the screen and the direction of motion were always coincident. Thus, the direction of motion was overspecified and should have been easier to detect than in the studies by Warren et al.

Second, global tau provides accurate passage information only if two conditions are met: The observer has to move at a constant velocity and the angle between the object and the direction of motion must not be too large. We always used constant-approach velocities, but one might be concerned that the law of small angles was violated in our displays. The largest angle between direction of motion and object (q) in our displays was presented in Experiment 2 (offset = 20 gu, distance to observer = 90 gu; i.e., 1.5 s from passage). In this condition, the true angle q deviated from its assumed value by 0.2°. Atan(offset/distance) measured 12.5°, whereas offset/distance = 0.22, or 12.7°. In the remaining conditions the error was even smaller. Thus, the error introduced by assuming atan(offset/distance) = offset/distance was small, that is, the law of small angles held for our displays. This calculation was confirmed by examining the global tau values until passage for objects offset by 5, 10, 15, and 20 gu (see Figure 11). It is evident that global tau remains robust until a short time before passage.

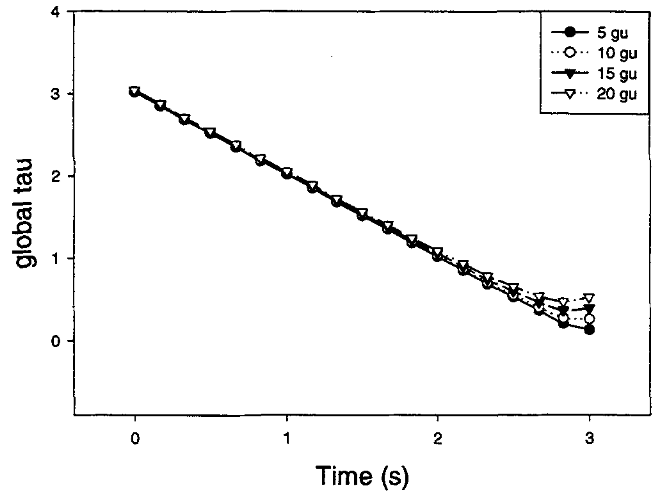

Figure 11. Global tau values for objects at an initial distance of 180 graphical units (gu) offset laterally by 5, 10, 15, and 20 gu. The objects approach the observer at a speed of 60 gu/s. The global expansion rate was calculated for differences in time of 16.67 ms, which corresponds to a frame rate of 60 Hz. The graph shows that time-to-passage as specified by global tau is accurate until 1 s before passage.

What Are the Limitations of Our Research?

In Experiments 3 and 4 we manipulated heading detection by varying gaze-movement and flow-field density. We found no influence of either factor, which suggests that a variable independent of heading accounts for performance. Although there is strong evidence that our manipulations were effective in manipulating heading thresholds (Crowell & Banks, 1993; Kaiser & Hecht, 1995; Warren et al., 1988), we did not confirm these findings in our research by soliciting heading judgments. Thus, the alleged relationship between heading detection and TTP judgments could not be directly evaluated. Possibly, our experimental manipulations were too crude to reveal a relationship between heading and TTP judgments. However, whatever the outcome of a more fine-grained analysis of heading–TTP relationships might be, we still found global tau to be overruled by simpler variables in the cases studied. Thus, that the visual system exclusively relies on global tau in passage scenarios was ruled out.

Another limitation of our research concerns the possible role of eye movements. Our displays either simulated gaze direction coinciding with the direction of motion or gaze being deflected from the direction of motion by a certain angle. In both cases, gaze was simulated to pass through the center of the screen. To achieve correspondence between simulation and actual retinal projection, observers' gaze had to be congruent with the simulated gaze direction (i.e., it had to be directed at the screen center). Following common practice, we did not control eye movements. Thus, the retinal projection will most likely deviate from the simulated projection. To our knowledge, no systematic attempts at determining the consequences of this deviation have been reported. However, one might argue that we did not obtain an effect of gaze-movement angle because simulated and actual retinal projection did not correspond. However, Kaiser and Hecht (1995) and Crowell and Banks (1993) did obtain effects of gaze-movement angle under similar conditions. Thus, an error introduced by uncontrolled eye movements would fail to explain the null effect of gaze-movement angle in Experiments 3–5.

The results in favor of image velocity as the effective information for arrival time were based on computer simulations that varied only optical information. In the presence of informative stereo, accommodation, and vergence, these extraretinal cues may well enter the process of TTP estimation (Heuer, 1993). Thus, it remains to be investigated whether the results will generalize to situations outside the laboratory.

Can Another Strategy Besides Tau and Image Velocity Explain the Data Better?

When direction of motion and direction of gaze are coincident, a straightforward strategy can predict relative TTP, namely the eccentricity of the target with respect to the center of the visual field (or the screen). As long as symmetric offset from the direction of motion is assumed, the more eccentric target is infallibly closer to the observer and will pass him or her first. Because such a symmetry assumption is often valid, the visual system might have gotten away with using such a plain eccentricity heuristic as a default. Compared with all other strategies, it requires the least amount of computation. Because this strategy is often indistinguishable from global tau or image velocity, we systematically decoupled the direction of motion and the direction of gaze in Experiments 3–5. When the direction of gaze was deflected to the right (left) of the direction of motion, targets on the left (right) of the direction of motion were always closer to the edge of the screen, irrespective of offset and distance in depth. Because the direction of gaze was deflected an equal number of times to the left and right, a strategy based on distance to the edge of the screen should have resulted in chance performance, which was clearly not the case.

Thus, in our displays observers did not use the simple eccentricity heuristic. Additional evidence against this heuristic comes from Kaiser and Mowafy (1993). They reported that observers used a contraction–expansion heuristic in which observers mapped angular contraction of two targets placed on the same side of the direction of motion on the judgment that the less eccentric target will pass first. Expansion was mapped on the judgment that the more eccentric target was to pass first. Consequently, observers did not always judge the more eccentric target to pass by first, but the target that was moving faster: If the angular separation between the targets is contracting (expanding), the target with the smaller (larger) eccentricity is moving faster. Thus, at this point, it is most probable that observers did not rely on the simple eccentricity heuristic but instead relied on the somewhat more sophisticated image velocity. Having ruled out one simpler strategy does not, of course, mean that there could not be others yet to be suggested. It is also conceivable, albeit difficult if not impossible to test, that observers switched strategies. They could have used a simple image-based heuristic as a default and resorted to complex strategies such as tau only when the stimulus was complex.

In summary, the results of our experiments demonstrate that observers were unable to make full use of the complex information that was provided by global tau. When two targets were asymmetrically placed at different depths within a 3-D cloud of point lights, TTP judgments were best explained by the image velocity. These findings are inconsistent with conclusions drawn in previous studies that did not distinguish between whether performance was based on tau or on image velocity. In our experiments, targets with a high image velocity were consistently perceived to be closer than targets with a low image velocity. Thus, when global tau information is present, the visual system does not default to making use of it. Rather, a simpler, presumably less expensive, strategy is adopted.

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