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Influence of Approach Angle on Estimates of Time-To-Contact

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Is the retinal periphery as capable of extracting time-to-contact information from a radially expanding optical flow field pattern as the retinal center? To address this proposition, two experiments were performed using both male and female participants viewing graphically generated scenes that depicted one road approaching directly towar them and a second road approaching from a 40° angle to their left. A vehicle could approach the observer along either road and was removed at various times before contact. Participants were required to estimate when the vehicle would have reached their position. Each experiment employed a 2 × 2 × 3 design in which sex was a between-subject variable while vehicle approach trajectory and either vehicle removal distance or vehicle approach velocity were within-subject variables. Results of the experiments indicate the retinal periphery is less sensitive to time-to-contact information than the retinal center. Variations in estimates of time-to-contact increased with vehicle removal distance and vehicle approach velocity while the accuracy of time-to-contact estimates increased with viewing time. In addition, with only a single approach velocity, the first experiment yielded no significant sex differences. However, when vehicle approach velocity was manipulated, significant sex differences emerged. The theoretical and practical ramifications of these results are presented.

Motor vehicle accidents represent the leading cause of years of life lost in the developed world (Transportation Research Board, 1990). With the spread of automobiles to the developing world, accidental collision threatens to become the leading cause of years of life lost (death before average life expectancy) globally. In 1993, 538 people lost their lives in the state of Minnesota in motor vehicle accidents (Minnesota Department of Public Safety, 1995). In the same year in the United States, 42,000 people lost their lives in motor vehicle accidents, and 2 million people

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experienced disabling injuries (National Safety Council [NSC], 1994). The total monetary cost to the United States due to these injuries and deaths was $167.3 billion (NSC, 1994). In more stark terms, one person died on average every 13 min, and every 16 sec a person suffered a major injury due to motor vehicle accidents in the United States. Because of this loss of life and the societal cost as a result of collisions, understanding the basic processes involved in the perception of imminent collision represents a vital real-world endeavor. At the same time, the phenomena involved in imminent collision have much to say concerning theoretical issues in ecological psychology (Gibson, 1986; Lee, 1976). What can be done to decrease the rates of death and disabling injuries due to motor vehicle accidents? A first step is to determine the description of motor vehicle accidents. Of the 42,000 deaths cited previously, 60% (25,300) were caused by collisions of various kinds, including collisions between motor vehicles; with fixed objects, and with bicycles, railroad trains, animals, animal-drawn vehicles, or streetcars. The remaining 40% (16,700) of the deaths stemmed from pedestrian accidents and noncollision accidents (NSC, 1994).

One area of research investigating the phenomenon of collisions has come to be known variously as arrival time (Caird & Hancock, 1994; DeLucia, 1991a; Law et al.,1993), time to arrival (Schiff & Oldak, 1990), time to collision (Cavallo & Laurent, 1988; Groeger & Cavallo, 1991; Hoffman & Mortimer, 1994; Lee, 1976; McLeod & Ross, 1983; Schiff & Detwiler, 1979), time to contact (Tresilian, 1991), time to go (Carel, 1961), and also time to passage (Kaiser & Mowafy, 1993). Based upon a taxonomy we have developed, we prefer time to contact (hereafter referred to as T_c), because in our studies, the participant is requested to determine the amount of time before collision with an approaching vehicle (Manser & Hancock, 1996).

The approach used in most studies examining T_c involves a display terminal or projection screen upon which the participants view an object approaching them on a head-on collision or a close by-pass trajectory (Caird & Hancock, 1994; Cavallo & Laurent, 1988; Groeger & Cavallo, 1991; Groeger, Grande, & Brown, 1991; Herstein & Walker, 1993; Hoffmann & Mortimer, 1994; Knowles & Carel, 1958; McLeod & Ross, 1983; Schiff & Detwiler, 1979; Schiff & Oldak, 1990; Schiff, Oldak, & Shah, 1992). At some point during the presentation, the approaching object "disappears." The participants' task then is to respond when they think the object would either have collided with them or passed next to them had it not disappeared. Previous experimentation has shown that individuals do not accurately judge T_c (e.g., Caird & Hancock, 1994; Cavallo & Laurent, 1988; Ellingstad & Heimstra, 1969). The findings of studies using this *removal paradigm* have revealed several consistent characteristics. One consistent finding, illustrated in Figure 1, is that individuals progressively underestimate T_c as actual T_c increases (Caird & Hancock, 1994; Carel, 1961; Hoffmann & Mortimer, 1994; Knowles & Carel, 1958; McLeod & Ross, 1983; Schiff & Detwiler, 1979; Schiff & Oldak, 1990; Schiff, Oldak, & Shah, 1992; Stoffregen & Riccio, 1990). Results of these studies

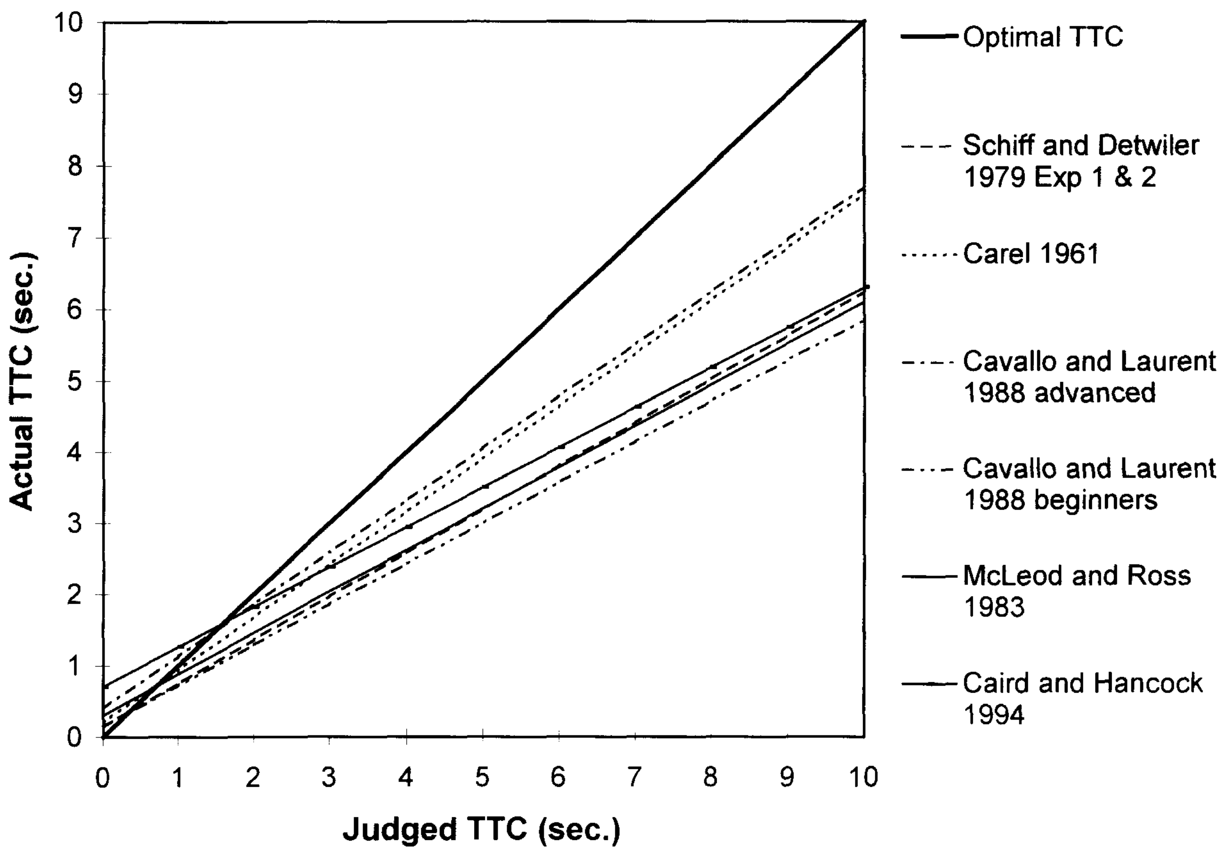

FIGURE 1 Results of previous T_c research for the cited studies. The collective findings show that participants underestimate T_c and that such underestimation grows with the absolute duration of actual T_c.

indicate that estimates of T_c are generally 60% of actual T_c and that in general, there is about 50% variability in estimates of T_c (Tresilian, 1995).

A second finding is that individuals are progressively more accurate estimating T_c with increased viewing time of the approaching object (e.g., Caird & Hancock, 1994; McLeod & Ross, 1983; Schiff & Oldak, 1991). However, note that the amount of time an individual is allowed to view an approaching object is systematically related to two other factors: the total viewing distance and the velocity of the approaching object. If any one of these variables is modified, one or both of the other variables are affected to some degree. Therefore, it is difficult to separate the effects of increased viewing time with the effects of increased viewing distances or manipulations of object velocity. Although the effects of any one variable cannot be separated from the effects of the other two variables completely, it is generally accepted that increased viewing time results in more accurate estimates of T_c. A less ubiquitous but frequently observed trend is that men and women differ in their estimate of when an object will collide with them. Caird and Hancock (1994), McLeod and Ross (1983), and Schiff and Oldak (1990) found that women are less accurate than men in estimating T_c as actual T_c increases. In addition, evidence suggests greater variability in womens' judgments of T_c than mens' (Caird & Hancock, 1994; McLeod & Ross, 1983; Schiff & Oldak, 1990). However, an exception is the work of Schiff, Oldak, and Shah (1992), who found no such sex differences. These collective findings emerged from the viewing configuration in which an object approached a person on a head-on collision course, or a person is approached by an object on a head-on collision course. As indicated by Stoffregen & Riccio (1990), when an object is approaching a person on a head-on collision course (0° trajectory) a radially expanding optical flow field pattern is generated on the retina. Of course, this situation also is true when an individual is approachiing an object.

Such studies indicate that the retinal center can use a radially expanding optical flow field pattern to specify T_c. But can the retinal periphery use a radially expanding optical flow field pattern to specify T_c? If an approaching object is moving towards a participant on a tangential trajectory (i.e., a collision course other than head on), a radially expanding optical flow field pattern would be generated on or very near the retinal periphery. Do the findings in the head-on trajectory T_c studies apply to alternate approach trajectories? Our work is directed toward answering this question.

In some allied work, Stoffregen and Riccio (1990) investigated the effects of a radially expanding optical flow field pattern on the retinal center and retinal periphery and proposed that, like the retinal center, the retinal periphery is sensitive to a radially expanding optical flow field pattern in specifying T_c. Participants in their experiment sat next to two computer monitors that were positioned 90° to each other. Participants viewed a computer-generated ball, appearing at different distances from them, approaching from either a head-on trajectory or a side trajectory traveling at different speeds. Unlike the removal paradigm, the ball appeared to travel all the way to the participant, whose task was to avoid collision by dodging out of the way at the last possible moment. The results from this *collision–avoidance paradigm* indicated that directional accuracy of movements and timing of collision–avoidance responses were superior for objects approaching from the front and not the side. Although their respective responses proved significantly different, the authors suggested that these differences could not be attributed to the pickup of the radially expanding optical flow field pattern specifying T_c due to experimental limitations. In addition, they emphasized that retinal center looming and retinal peripheral looming were more similar than different. Consistent with previous findings (e.g., Caird & Hancock, 1994; Carel, 1961; Cavallo & Laurent, 1988; McLeod & Ross, 1983; Schiff & Detwiler, 1979; Schiff & Oldak, 1990), the results of Stoffregen and Riccio's experiment indicated participants increasingly underestimated (preceded) the actual moment of impact as the actual T_c increased. For the front monitor condition (head-on trajectory), the line of best fit generated had a slope of .89 and for the side monitor condition (side trajectory) the slope was .85. These values were considerably higher than those obtained with the removal paradigm. In particular, Caird and Hancock (1994), Carel (1961), Cavallo and Laurent (1988), McLeod and Ross (1983), and Schiff and Detwiler (1979) obtained slope values of .56, .74, .73, .58, and .61, respectively. Stoffregen and Riccio (1990) suggested the high slope values obtained in their experiment could be due to the increased duration of the visual stimulus provided and/or the type of responses required of participants in the study. This conclusion is warranted because estimates of T_c increased with greater viewing time as experienced in their experiment and as indicated earlier. Stoffregen and Riccio did not engage in an examination between sexes, so a comparison of sex between their results and the results of other time-estimation studies is not possible.

A direct comparison of results from the removal and collision-avoidance paradigms should be made with caution for several reasons. First, the collision-avoidance paradigm requires a participant to avoid collision physically, unlike the removal paradigm, which typically requires a mere button press. Second, the collision-avoidance paradigm frequently permits greater viewing time, because the approaching object appears to travel the entire distance to the participant, compared to the typical curtailment of viewing time with removal. The collision-avoidance paradigm used by Stoffregen and Riccio (1990) is a variation of a relative-judgment timing skill (Tresilian, 1995) and, therefore, different from the removal paradigm, which contains a significant empty time-estimation component. Consequently, the slope values obtained by Stoffregen and Riccio (1990) might be a result of their increased viewing time.

Given the foregoing concerns and limitations, the effect of variations in approach trajectories on an individual's ability to estimate accurately T_c remains in question. Consequently, the purpose of our investigation was to examine the sensitivity of the retinal periphery and the retinal center to a radially expanding optical flow field pattern, specifying T_c under traditional removal conditions. Further, we sought to confirm previously observed removal effects and to address the still uncertain influence of participant sex upon these abilities.

EXPERIMENT 1

Method

Participants. Ten men and ten women recruited from faculty, staff, and student body at the University of Minnesota participated in this study. All participants were between 18 and 32 years of age, possessed normal (20/20) or corrected-to-normal vision with contact lenses, and possessed a valid State of Minnesota or State of Wisconsin driver's license. Participants received no monetary compensation, class credit, or other benefits from partaking in this study. Both men and women were under study because previous T_c research has indicated that participant sex may be an internal factor affecting estimates of T_c.

Apparatus. The environment for this experiment consisted of two walls intersecting at a right angle, with the initial 240 cm of each wall used. On each wall, a computer-generated driving scenario was projected. The driving scenarios were generated by Coryphaeus Easy Scene® computer software, supported on a Silicon Graphics® Onyx computer, and projected through two Electrohome ECP–3100® projectors. The two images were synthesized so that the images covering each wall appeared to be part of one greater image creating a field of view of 40° vertically × 95° horizontally as measured from the participant's head position. Responses were collected via a Nighthawk® 4402 data collection computer connected to a hand-held button switch.

Procedure. Upon signing the Human Subjects Consent form, participants were provided with instructions for the study. Participants then were seated 230 cm from the front wall and 230 cm from the side wall (on the participant's left). They faced forward and were instructed to look straight ahead at the front view of the computer-generated scene at all times. The computer-generated scene depicted a Y-shaped intersection. The road the participant was on extended directly forward 640 m. Immediately to the left of the participant, the computer-generated scenario depicted a second road extending away from the participant for 640 m at an angle of 40° to the front road. We positioned the road at a 40° angle to ensure that the image of the approaching vehicle would be generated on the periphery of the retina and so participants could view the image approaching from the side binocularly while looking forward. These conditions are similar to real-life situations where a driver is at a Y intersection waiting to make a left turn. At 47 m in front of the driver, a stranded vehicle (an Izuzu Rodeo) had its emergency lights flashing. Participants were instructed to fixate their gaze on the stranded vehicle at all times during all trials. No other procedures were conducted to ensure participants looked at the stranded vehicle at all times.

One concern was that participants' head position and eye gaze were not controlled in Experiment 1 (or Experiment 2), and this may have allowed participants to "look" directly at the vehicle when it approached on the 0° *and* the 40° vehicle-approach trajectories. The result of this participant behavior would be the generation of a radially expanding optical flow field pattern on the center of the retina regardless of vehicle approach trajectory, and would, in theory, confound the results of the experiment and lead us to the conclusion that the results would be tainted. However, if participants did partake in this behavior, it would only serve to equate the estimates of T_c between the 0° and 40° vehicle approach trajectories, and consequently reduce the power of the experiment. All participants viewed identical driving scenarios depicting a Porsche 911 appearing 200 m away from the participant on one of the two roads and then approaching the participant on a collision course at a constant velocity of 13.41 m/sec. The approaching vehicle subtended a vertical visual angle of .25° when it first appeared in the driving scene. The approaching vehicle was then removed from the driving environment either 80.46 m (6 sec), 60.34 m (4.5 sec), or 40.23 m (3 sec) prior to collision. The approaching vehicle subtended final vertical visual angles of either 1.29°, 1.78°, or 2.87°, respectively when it disappeared. These kinematic conditions resulted in total viewing times of 8.92, 10.42, and 11.92 sec, respectively. We chose to manipulate removal times between 2 and 10 sec due to indications of floor and ceiling effects in peoples' ability to estimate T_c. Specifically, as indicated in Figure 1, there appears to be unity between judged T_c and actual T_c at about 1.5 sec, whereas Schiff and Detwiler (1979) suggested that people can use optically specified T_c information, but a ceiling to this ability may exist at around 10 sec.

Participants performed one practice trial, depicting the vehicle approaching on a 0° angle of incidence and disappearing from the scene three seconds before collision. Participants were instructed to press a handheld button with their thumb when they believed the approaching vehicle would have collided with them. Again, participants were told to fix their gaze at the stranded vehicle directly in front of them at all times and were not given feedback regarding their performance. The independent variables were the trajectory of the approaching vehicle (0° or 40°), the distance at which the approaching vehicle was removed from the driving environment (80.46, 60.34, and 40.23 m prior to collision), and the sex of the participant. The primary dependent variable was the participant's T_c response. All participants performed 10 trials of each condition with a 1-min break after every 15 trials. All 60 trials were randomized for each participant to reduce the possibility of confounds from order-of-trial presentation.

Design. Estimates of T_c were analyzed in a 2 × 2 × 3 (Sex × Vehicle Approach Trajectory × Vehicle Removal Distance) mixed analysis of variance (ANOVA) with sex as a between-subject variable and vehicle approach trajectory (0° and 40°)

and vehicle removal distance (40.23, 60.34, and 80.46 m prior to collision) as the within-subjects variables. Derived dependent variables were overall accuracy in performance (absolute error), response bias (constant error), and response consistency (variable error). The alpha level was set at .05 and significant differences were distinguished using Tukey's honestly significant difference (HSD) post hoc test.

Results

Absolute error. Absolute error values provide an indication of the overall accuracy of the participants' performance without regard to directional bias (Schmidt, 1988). Results for absolute error indicated that participants' overall accuracy in estimating T_c decreased significantly as the vehicle removal distance was increased, $F(2, 36) = 48.26, p = < .01$. The means were 4.51, 6.92, and 10.43 sec for the 40.23-, 60.34-, and 80.46-m vehicle removal distances, respectively. Post hoc analysis indicated each condition differed significantly from the others.

Constant error. Constant error provides an indication of the participants' average response error and the directional bias of these errors (Schmidt, 1988). Results of the constant error analysis revealed a significant main effect for vehicle approach trajectory, a significant main effect for vehicle removal distance, and a Vehicle Approach Trajectory × Vehicle Removal Distance interaction. The significant main effect for vehicle approach trajectory, $F(1, 18) = 15.94, p < .01$, indicated less bias for the 0° vehicle approach trajectory at –2.71 sec, compared with that for the 40° vehicle approach trajectory at –5.17 sec. These results provide evidence that participants can extract visual T_c information with significantly less bias when such information is generated on the retinal center. In addition, the negative mean value of each mean represents an underestimation of T_c across all vehicle removal distances, which confirms previous observations on such responses.

There was a significant vehicle removal distance effect for the constant error that indicated participants estimated Tc with significantly less bias when the vehicle was removed at closer distances, $F(2, 36) = 13.59, p < .01$. The mean for the 40.23-m vehicle removal distance was –1.38 sec; the mean for the 60.34-m vehicle removal distance was –3.80 sec; and the mean for the 80.46-m vehicle removal distance was –6.64 sec. Post hoc analyses indicated the 40.23- and 60.34-m vehicle removal distances were significantly different from the 80.46-m vehicle removal distance.

Last, there was a Vehicle Approach Trajectory × Vehicle Removal Distance interaction, $F(2, 36) = 6.41, p < .01$. This interaction is illustrated in Figure 2 and indicates that participants underestimated T_c to a greater extent when the approaching vehicle was removed at greater distances, and the differences between the trajectory means diminished as the vehicle was removed at closer distances. There were no other significant main effects or interactions for constant error.

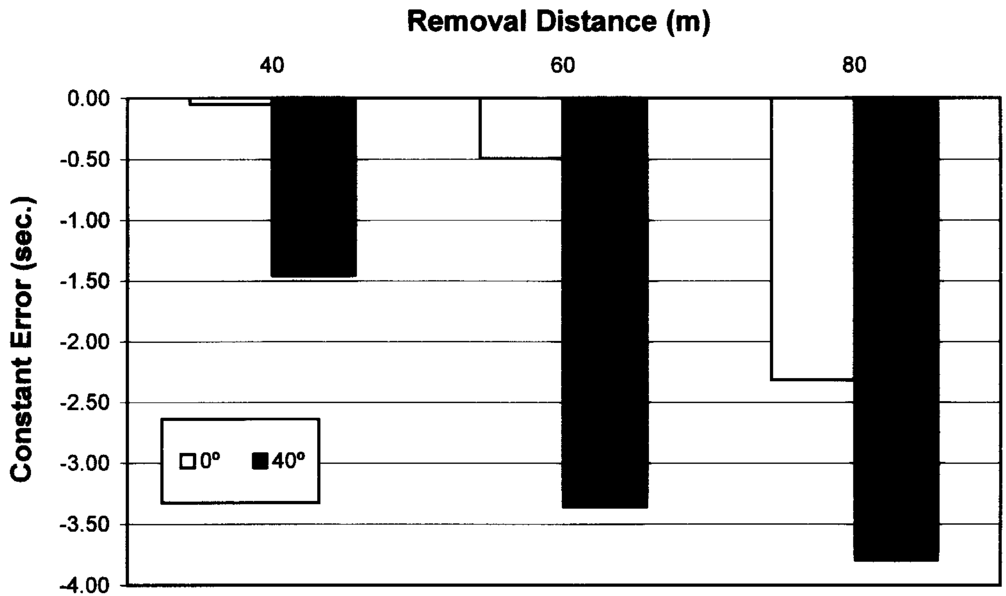

FIGURE 2 Interaction between vehicle removal distance and angle of approach in constant error. Note that constant error grows little between 40 and 60 m for the 0° approach angle but grows considerably for the 40° approach angle.

Variable error. Variable error represents the consistency of the participants' responses (Schmidt, 1988). The results of the variable error analysis indicated a significant vehicle removal distance effect, and a vehicle approach trajectory by vehicle removal distance interaction. The main effect for vehicle removal distance indicated that such variability increased significantly with vehicle removal distance, $F(2, 36) = 6.57, p < .01$. Means for the 40.23-, 60.34-, and the 80.46-m removal distance were 2.47, 3.16, and 4.27 sec respectively. Post hoc analysis revealed significant differences between the 40.23-m vehicle removal distance and the 80.46-m removal distance variability means.

The second significant finding for variable error was a Vehicle Approach Trajectory × Vehicle Removal Distance interaction, $F(2, 36) = 5.08, p = .01$. This effect is illustrated in Figure 3. The difference in variability means between the 0° and the 40° trajectory is minimal when the approaching vehicle is removed at 40.23 m; however, at a vehicle removal distance of 60.34 m, the difference in variability between the 0° trajectory and the 40° trajectory is large. Then at the 80.46-m vehicle removal distance, the variability in estimates of T_c are again minimally different. It

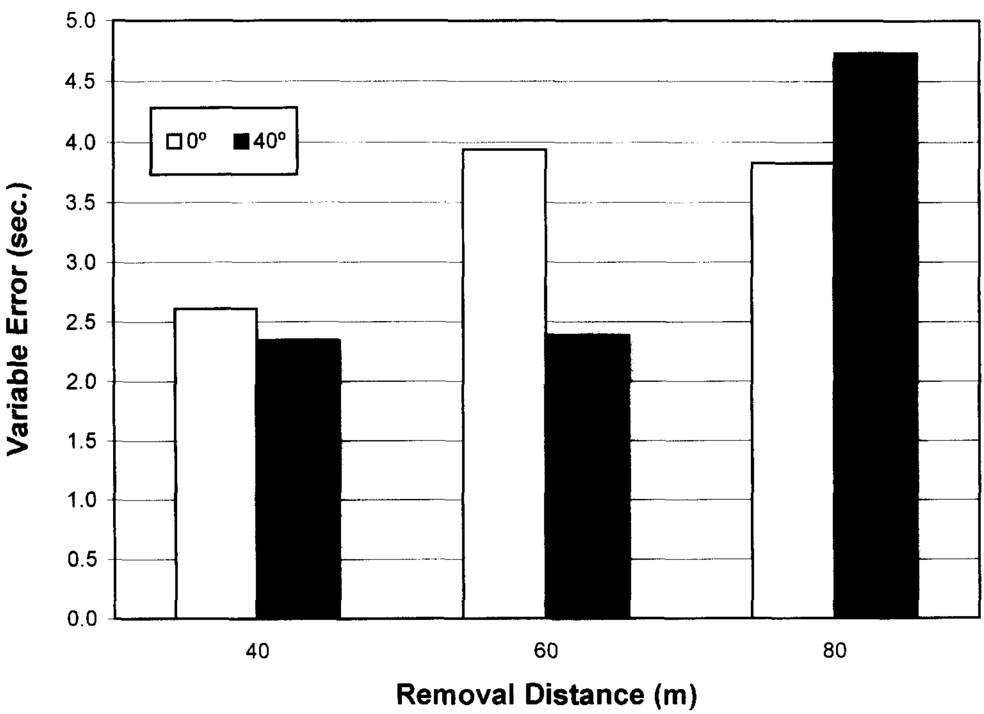

FIGURE 3 Interaction between vehicle removal distance and approach angle for variable error. The interaction arises from the sudden increase in variability at 60 m for the 0° versus the 40° approach angle.

is noteworthy that when the vehicle is removed from the environment at 40.23 or 60.34 m, the variability for the 0° vehicle approach trajectory is higher than the 40° trajectory; however, when the vehicle is removed from the environment at 80.46 m, the variability is greater for the 40° vehicle approach trajectory. No other significant main effects or interactions were present in variable error.

Summary of results. Overall results of the experiment indicated that participants were more accurate in estimating T_c when an object approached on a 0° head-on trajectory versus a 40° trajectory, were more accurate estimating T_c when the object was removed from the environment at shorter distances, and their T_c estimations become increasingly varied as the vehicle was removed at greater distances. The lack of a significant main effect or significant interaction for participant sex indicated women and men did not differ in their ability to estimate T_c under the conditions investigated.

Discussion

Kinematic parameters. The principal finding of this experiment was a significant difference in the estimate of T_c contingent on the vehicle's angle of approach. As indicated, participants were not as accurate estimating T_c when the vehicle was approaching from the side trajectory. This result provides evidence that the retinal periphery is less capable than the retinal center in extracting T_c information provided by a radially expanding optical flow field pattern. Although Stoffregen and Riccio (1990) also found significant differences between the retinal periphery and the retinal center, they suggested that the differences between the two areas of the retina were not due to the ability to extract T_c information from the radially expanding optical flow field pattern. The results of this study, contrary to the conclusions but not the results of Stoffregen and Riccio (1990), indicate that different areas of the retina are differentially sensitive to a radially expanding optical flow field pattern specifying when an object will collide with the self.

Our results also provide further support for several other T_c characteristics. The first is that participants underestimate T_c progressively as the approaching vehicle disappears at greater distances (Cavallo & Laurent, 1988; McLeod & Ross, 1983; Schiff & Detwiler, 1979). The second characteristic confirmed here is that participants' responses become progressively more varied as the vehicle disappears at greater distances and when viewing time decreases (Schiff & Oldak, 1990; Stoffregen & Riccio, 1990). The third and final characteristic confirmed here is that the ability to estimate T_c accurately is enhanced through an increase in viewing distance or viewing time (see also Caird & Hancock, 1994; Schiff & Oldak, 1990).

Sex differences. The absence of sex differences in this experiment is of particular interest. As noted, several previous studies had found a sex difference in

T_c estimates (Caird & Hancock, 1994; McLeod & Ross, 1983; Schiff & Oldak, 1990), although Schiff et al. (1992) did not confirm this. In each of the cited experiments reporting significant sex differences, the actual T_c was manipulated, and the size of the sex difference grew in proportion to T_c in an interactive manner. However, in the present experiment, there was only a single T_c; hence, the comparison is between the sexes at this single condition. It may be that the difference at this one brief T_c is insufficiently large to register a significant difference. As a consequence, we do not conclude from these that there are no sex differences in this ability. Indeed, our companion findings have shown substantive sex differences in a capability directly related to T_c in the removal paradigm (Hancock, Arthur, Chrysler, & Lee, 1994). Rather, it is probable that significant sex differences occur only beyond certain kinematic conditions in more prolonged times-to-contact as explored hereafter.

Individual differences. The inaccuracy in T_c estimation tends toward the side of safety. For example, if the T_c for the approaching automobile is 7 sec and the participant estimates collision will occur in 5 sec, there are an additional 2 sec in which the driver can reevaluate the situation and take action. Overestimations of T_c do not allow the luxury of reevaluation. Examining the mean results of the present experiment indicate that participants underestimated T_c for both approach trajectories and all three vehicle removal distances. However, such results can be misleading; for example, descriptive statistics indicate that 273 of 1,200 (or 22%) of all participant responses were overestimations. In addition, if we look in more detail at these data, we find that 16 participants overestimated less than 30% of their trials, whereas the remaining 4 participants overestimated in at least 70% of the total number of trials they performed. Indeed, if underestimating is erring on the side of safety, whereas overestimating is erring on the side of danger, all participants, but especially the noted four, would appear to be at considerable risk for collision. On these findings, examining the percentage of trials participants over- or underestimated provides only a limited perspective. To understand individual differences in still more detail, we have plotted the average amount of time in seconds each participant either over- or underestimated actual T_c (see Figure 4). Of particular interest is that of the four participants who overestimated actual T_c 70% of the time, only two had average T_c estimations nearly a full second after actual collision would have occurred. Therefore, we can confirm the observations of Schiff and Oldak (1990) concerning large individual differences in this capability.

EXPERIMENT 2

Experiment 2 was a direct extension of Experiment 1. The primary purpose was to evaluate central versus peripheral T_c using different approach velocities. First, we sought to replicate the findings obtained from differing vehicle approach trajectories

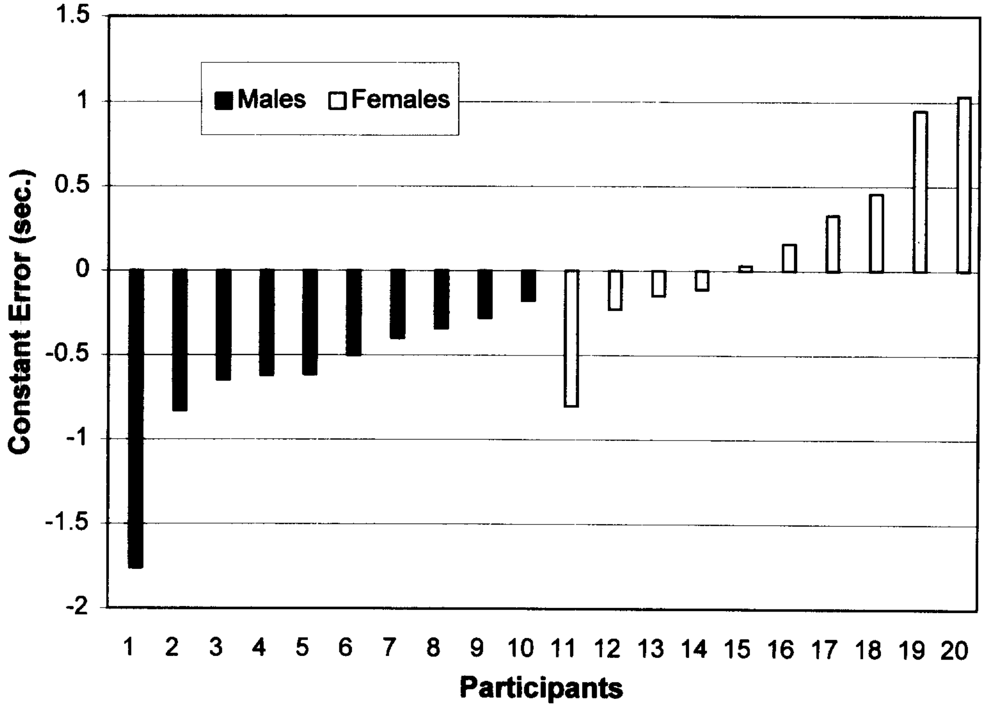

FIGURE 4 Constant error means for each participant. Note that the order of participants on the figure do not reflect the order in which participants performed the experiment.

observed in Experiment 1 and to determine if, as indicated by the statistical results provided by Stoffregen and Riccio (1990), the retinal center and the retinal periphery are not equally sensitive to T_c information. Our hypothesis was that participant responses would be more accurate, more consistent, and contain less bias when the vehicle approaches from the 0° trajectory and at higher velocities. The latter hypothesis is in line with previous observations that indicate participants' estimates of T_c are more accurate and consistent when the approaching object is traveling at higher velocities (McLeod & Ross, 1983; Schiff, Oldak, & Shah, 1992). Second, we sought to determine if the lack of any sex effect or interactions for response accuracy, bias, and consistency in Experiment 1 were due to the specific kinematic conditions selected. We postulate that female estimates of T_c would be less accurate, contain more negative bias, and be more varied than male estimates of T_c when the vehicle approaches from a 0° trajectory and from a 40° vehicle approach trajectory. In addition, the differences between male and female estimates of T_c would decrease when the velocity of the approaching vehicle is greater. Third, in Experiment 2, the velocity and the vehicle removal distance of the approaching vehicle was manipulated to hold viewing time constant. This was structured to determine if the removal effects obtained in Experiment 1 were due solely to increases in viewing time of the approaching vehicle.

Method

Participants. Twenty new participants were recruited according to the criteria and characteristics set forth for Experiment 1.

Apparatus. The apparatus used for this study was a high-fidelity wrap-around environment simulator (WES). The WES was a large sphere with the bottom third removed, measuring 3.65 m in height, 4.72 m in width at floor level, and 5.48 m at the widest point. The WES consisted of a steel and wooden infrastructure onto which eight white fiberglass screens were affixed. Each screen was 243.84 cm tall extending up from the floor and was synthesized with adjacent screens so that it appeared as if there was one single screen wrapping 360° around the participant. The driving scene presented to participants was created by Coryphaeus Easy Scene® computer software, generated by a Silicon Graphics Onyx computer, and projected through three Electrohome® ECP–3100® projectors to the curved wall of the WES. The three separate images were synthesized so that they appeared to be one complete image that subtended a 165° horizontal useful field of view and a 55° vertical useful field of view for the participant. Participant responses were collected via a Nighthawk® 4402 data collection computer connected to a handheld button switch. For a depiction of this scenario, see Figure 5.

Procedure. Participants were presented with and signed the Human Subjects Consent form and were given directions regarding this specific study. Participants then were seated on a standard 45.72-cm tall chair located in the center of the WES. At all times, participants faced the center of the scene and were instructed to look forward. The driving scenario then was projected to the curved wall. The driving scenario was identical to the computer-generated scene used in Experiment 1, except more of the driving scene was available for viewing. In this environment, the stranded vehicle subtended a vertical visual angle of 1.72°. Like Experiment 1, this scenario allowed a vehicle to approach the participant on a collision course at either a 0° trajectory (same road) or a 40° trajectory (left road). This produced a radially expanding optical flow field pattern on either the retinal center or the retinal periphery as the subject viewed the stranded vehicle. The situation allowed the image of the approaching vehicle to be viewed binocularly from both approach trajectories.

The scenario then depicted a vehicle (Porsche 911) approaching the participant on a collision course from either the 0° trajectory (road directly in front of them) or from the road to their left. The approaching vehicle traveled at a constant velocity of either 20.11 m/sec (45 mph), 17.88 m/sec (40 mph), or 15.64 m/sec (35 mph) and was removed from the scene at either 22.96, 42.63, or 62.30 m before collision.

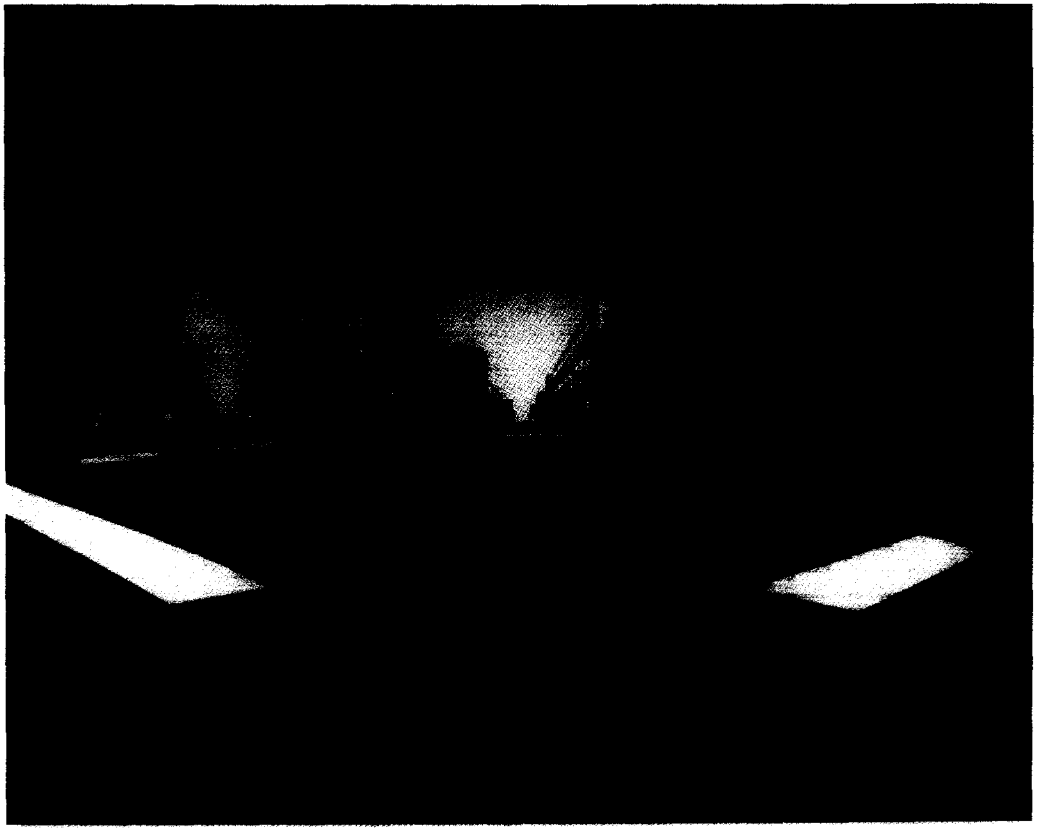

FIGURE 5 Depiction of the driving scenario. Note that this is only an approximation of the actual scene. There are inherent limitations in viewing three-dimensional surfaces in a two-dimensional representation.

The final subtended vertical visual angles of the approaching vehicle when it was removed from the scene at 22.96, 42.63, and 62.30 m were 0.85°, 1.14°, and 2.0°, respectively. This configuration allowed total viewing time of the approaching vehicle to be held constant across all three conditions at 8.8 sec. The participants' task was to press a handheld button when they felt the vehicle would have collided with them had it continued traveling down the road.

The manipulation of velocity permitted equivalent viewing times for all conditions that effectively controlled for the effects of increased viewing time on estimates of T_c. The influence of increased viewing time on estimates of T_c may have been a significant factor contributing to the increased accuracy of T_c estimates in the first experiment and in research performed by Stoffregen and Riccio (1990). T_c also was systematically varied in this experiment by manipulating the approaching vehicle's velocity to determine if T_c varied for men and women, specifically, for the 20.11-, 17.88-, and 15.64-m/sec conditions, which produced actual times before collision of 1.14, 2.38, and 3.98 sec, respectively.

Participants performed two practice trials. The first practice trial depicted the vehicle approaching the participant on a 0° trajectory traveling at 20.11 m/sec and disappearing 22.96 m before collision, whereas the second practice trial depicted the vehicle approaching from the 40° trajectory at a velocity of 15.64 m/sec and disappearing 62.30 m before collision. The independent variables were trajectory of the approaching vehicle (0° or 40°), the velocity of the approaching vehicle (20.11, 17.88, or 15.64 m/sec), and the sex of the participant. The dependent variable was the participants' judged T_c. Participants then performed 10 trials in each of the six experimental conditions with a one minute break after each 20 trials. The 60 experimental trials were randomized for each participant.

Design. Estimations of T_c were analyzed in a 2 × 2 × 3 (Sex × Vehicle Approach Trajectory × Vehicle Approach Velocity) mixed ANOVA with sex as a between-subject variable and vehicle approach trajectory (0° and 40°) and vehicle approach velocity (20.11, 17.88, and 15.64 m/sec) as the within-subjects variables. The derived dependent variables were overall accuracy in performance (absolute error), response bias (constant error), and response consistency (variable error). The alpha level was set at .05 and significant differences were distinguished using Tukey's HSD post hoc test.

Results

Absolute error. The absolute error analysis indicated a significant main effect for vehicle approach trajectory, a significant effect for vehicle approach velocity, a significant Sex × Vehicle Approach velocity interaction, and a significant Vehicle Approach Trajectory × Vehicle Approach Velocity interaction. The main effect for vehicle approach trajectory, $F(1, 18) = 7.48$, $p = .01$, indicated participants estimated actual T_c with significantly less error when the vehicle approached from the 0° trajectory versus the 40° trajectory. The absolute error mean for the 0° and 40° trajectories were .79 and 1.04 sec, respectively. This provides initial indications that the retinal center is more sensitive than the retinal periphery to a radially expanding optical flow field pattern specifying the amount of time before collision will occur. There was also a main effect for vehicle approach velocity, $F(2, 36) = 46.91$, $p < .01$. The means for the 20.11, 17.88, and 15.64 m/sec vehicle approach velocity were .53, .80, and 1.40 sec, respectively. Post hoc analysis indicated the 15.64 m/sec vehicle approach velocity was significantly different from the 17.88 and the 20.11 m/sec vehicle approach velocity. A Sex × Vehicle Approach Velocity interaction was evident, $F(2, 36) = 13.76$, $p < .01$. This interaction is displayed in Figure 6 and indicates that when the approaching vehicle traveled at lower velocities, women's estimates of T_c were less accurate than men's. However, when the velocity of the approaching vehicle is greater, the accuracy of both men's and women's estimates of T_c increases and become nearly identical.

Although not significant, it is interesting to note women's estimates of T_c were less accurate than men for both the 15.64 and 17.88 m/sec vehicle approach velocity, but at the highest vehicle approach velocity (20.11 m/sec), men were not

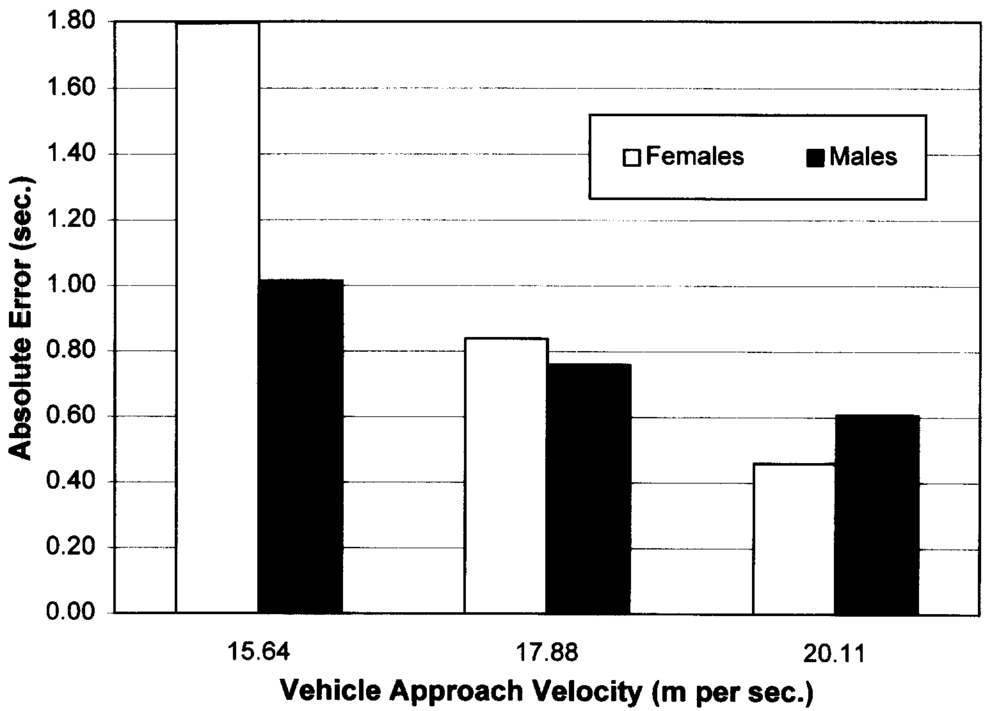

FIGURE 6 Sex × Vehicle Approach Velocity interaction for absolute error. The source of the interaction is due to the increase in the accuracy of women's estimates of T_c with increasing vehicle approach velocity.

as accurate as women in estimating actual T_c. A Vehicle Approach Trajectory × Vehicle Approach Velocity interaction was detected, $F(2, 36) = 4.68, p = .01$. The interaction is displayed in Figure 7 and indicates that estimates of T_c for the 0° and the 40° trajectory became more accurate and more similar as the vehicle approach velocity increased. No other main effects or interactions were found.

Constant error. Results of the constant error analysis revealed a significant effect for sex, a significant effect for vehicle approach trajectory, a significant effect for vehicle approach velocity, a Sex × Vehicle Approach Velocity interaction, and a Vehicle Approach Trajectory × Vehicle Approach Velocity interaction. The significant effect for sex, $F(1, 18) = 12.17, p < .01$, indicated that both men and women underestimated; however, the mean response bias for men at –.14 sec was significantly less than the mean response bias for women at –.52 sec. The significant effect for vehicle approach trajectory, $F(1, 18) = 7.68, p = .01$, indicated that participants responded with less bias when the vehicle approached from the 40° trajectory than when the vehicle approached from the 0° (head-on) trajectory. Average response bias for the 40° vehicle approach trajectory and the 0° trajectory were –.09 and –.36 sec, respectively. Post hoc analysis of the significant effect for vehicle approach velocity $F(2, 36) = 38.45, p < .01$, indicated the 30-mph mean (–.75 sec) vehicle approach velocity was significantly different from both the 35-mph (–.06 sec) and the 40-mph (.13 sec) mean vehicle approach velocities. In addition to the significant effect for vehicle approach velocity, there was a Vehicle Approach Velocity × Sex interaction, $F(2, 36) = 5.58, p < .01$. This interaction is illustrated in Figure 8. The interaction indicates that when the approaching vehicle traveled at lower velocities, women substantially underestimated the actual T_c compared to men, and with increased velocities the accuracy of these estimates for men and women became similar.

A Vehicle Approach Trajectory × Vehicle Approach Velocity interaction was also revealed, $F(2, 36) = 3.21, p = .052$. As indicated by Figure 9, this interaction indicates when the vehicle approached at the lowest velocity T_c was underestimated to a greater degree than when the vehicle approached at a 0° trajectory, but as the vehicle approach velocity was increased, estimates of T_c more closely approximated actual T_c for both trajectories. Worth noting is the fact that when the vehicle approach velocity was highest there were slight but systematic overestimates of T_c for both approach trajectories. No other main effects or interactions were found.

Variable error. Results of the variable error analysis revealed a main effect for vehicle approach trajectory, a main effect for vehicle approach velocity, and a significant Vehicle Approach Trajectory × Vehicle Approach Velocity interaction. The main effect for vehicle approach trajectory, $F(1, 18) = 12.90, p < .01$, indicated that participants responded with significantly less variability when the vehicle approached from the 0° trajectory as opposed to a 40° trajectory. The mean for

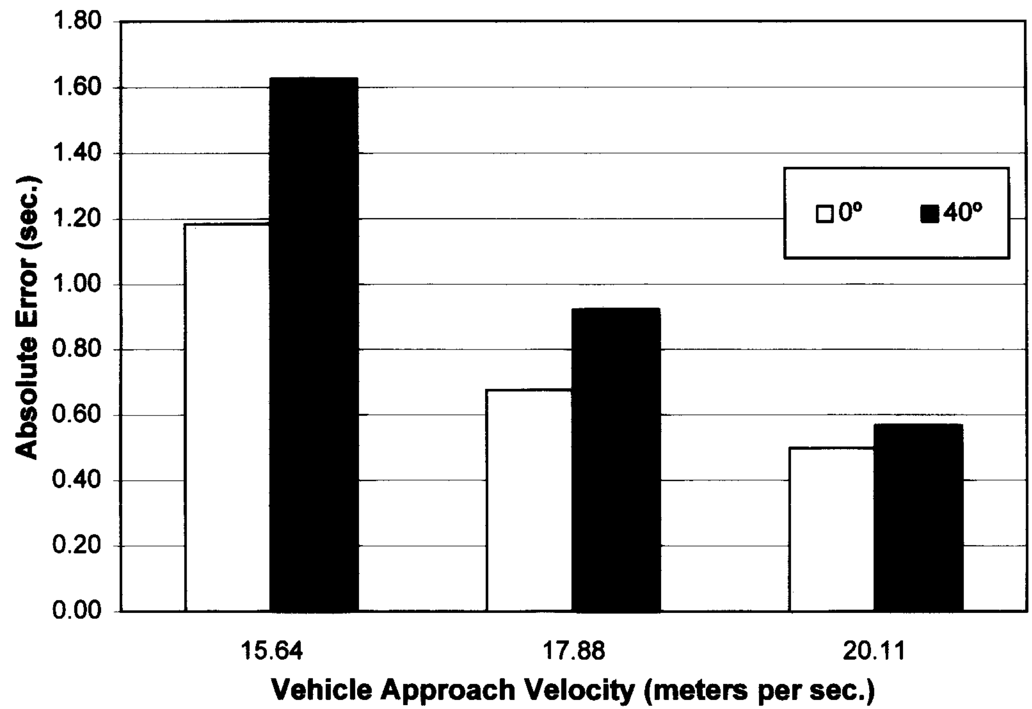

FIGURE 7 Interaction between vehicle approach trajectory and vehicle approach velocity for absolute error. Note that when the vehicle approach velocity is increased for both approach trajectories, there is also an increase in estimates of T_c.

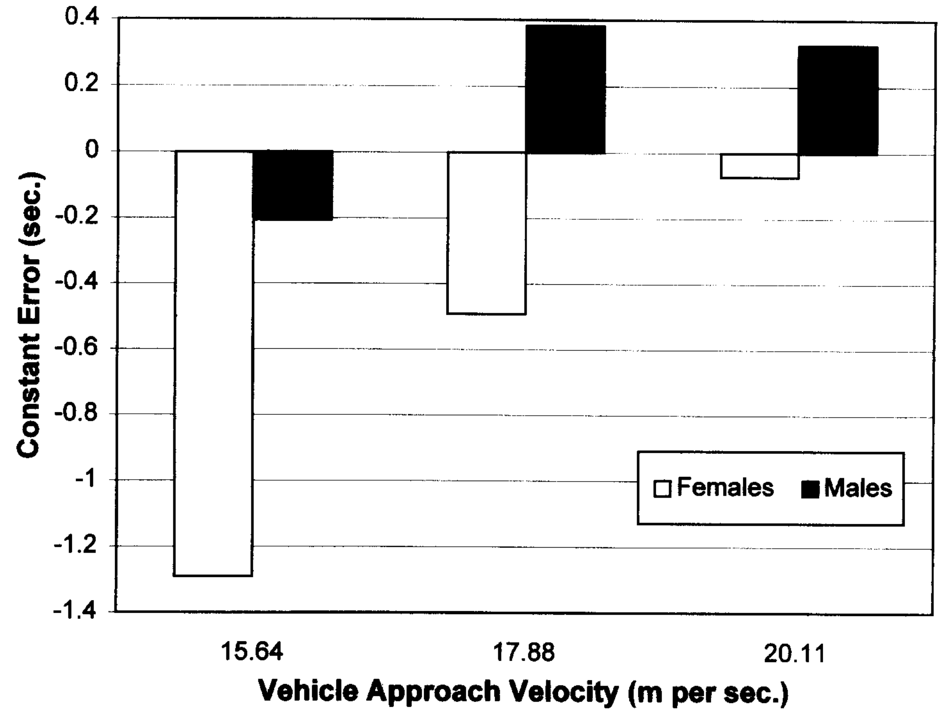

FIGURE 8 Vehicle Approach Velocity × Sex interaction for constant error. The interaction is a result of a decrease in women's underestimations of T_c as the vehicle approach velocity increased.

the 0° vehicle approach trajectory was .49 sec, whereas the mean for the 40° approach trajectory was .99 sec. This result indicates the retinal periphery is less consistent than the retinal center for extracting T_c information from a radially expanding optical flow field pattern. The second variable error finding was that participants responded with less variability when the approaching vehicle traveled at higher velocities. Specifically, post hoc analysis indicated a significant difference between the 15.64 m/sec vehicle approach velocity with a mean of 1.09 sec and the 20.11 m/sec vehicle approach velocity possessing a mean of .40 sec. The Vehicle Approach Trajectory × Vehicle Approach Velocity interaction, $F(2, 36) = 7.64, p < .01$, indicates that when the vehicle approached at 15.64 meters per second responses for the 40° vehicle approach trajectory were much more varied than the 0° vehicle approach trajectory but these differences dissipated when the approaching vehicle's velocity was increased to 20.11 m/sec (see Figure 10). No other main effects or interactions were evident in the variable error analysis.

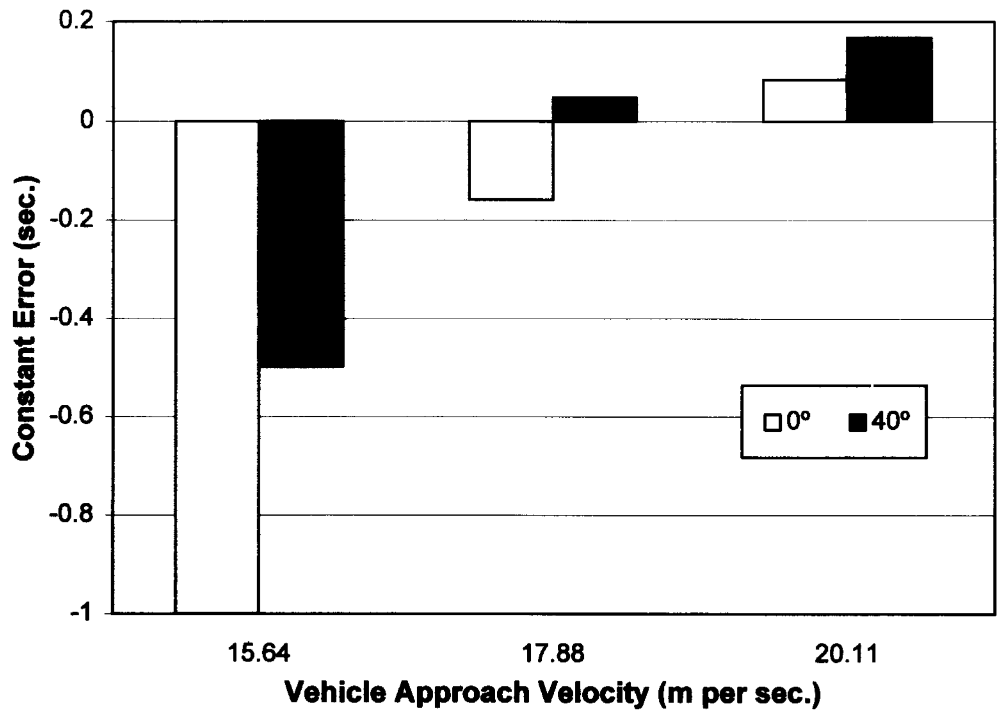

FIGURE 9 Vehicle Approach Trajectory × Vehicle Approach Velocity interaction for constant error. Note that when the vehicle approach velocity was highest, there were overestimates of T_c for both of the approach trajectories.

Summary of results. Overall, the results of this study indicated participants were more accurate estimating T_c when the vehicle approached from the 0° trajectory and possessed less variability estimating T_c when the vehicle approached from the 0° trajectory. Participants also were able to estimate T_c with greater accuracy and less variability when the vehicle approached the participant at the highest velocity tested. In addition, as indicated by a significant main effect and two significant interactions, sex differences in the ability to estimate T_c were confirmed. In general, the differences between men's and women's estimates of T_c were most pronounced when the approaching vehicle velocity was low and diminished when the approaching vehicle's velocity was at its maximum.

Discussion

Kinematic parameters. The principle finding of Experiment 2 was that participants' estimates of T_c were not as accurate and more varied when the vehicle approached from a 40° trajectory than when the vehicle approached from a 0° trajectory. These results, in addition to similar results in Experiment 1 and the statistical results obtained by Stoffregen and Riccio (1990), indicate the retinal periphery is less able to extract T_c information from a radially expanding optical flow field pattern specifying the amount of time before contact will occur.

One result in Experiment 2 that differs from Experiment 1 is the constant error main effect for vehicle approach trajectory. The results from Experiment 1 indicated less response bias when the vehicle approached from the 0° trajectory versus the 40° trajectory, but in Experiment 2, participants responded with less bias when the vehicle approached from the 40° trajectory. The source of this change for constant error scores in Experiment 2 comes from the performance of women when the vehicle approached from the 40° trajectory. Specifically, in Experiment 1 the constant error mean for women when the vehicle approached from the 0° and the 40° vehicle approach trajectories were –.12 and –3.6 sec, respectively. However, in Experiment 2 the constant error means for women for the 0° and the 40° vehicle approach trajectories were .01 and .32 sec, respectively. The reason for this change may be due to the increase in useful field of view for Experiment 2. The change may also be due to the increase in approach velocity for the vehicle in Experiment 2. However, our contention that the retinal center is more capable of extracting T_c information than the retinal periphery is supported due to the consistent absolute error results between the two experiments.

The results of this study also confirm several other T_c phenomena. First, estimates of T_c become more accurate, less biased, and more consistent as the velocity of the approaching vehicle is increased. The results confirming effects for differing vehicle approach velocities are robust and should not be dismissed due to the possible confounding effects caused by differing viewing distances of the approaching vehicle.

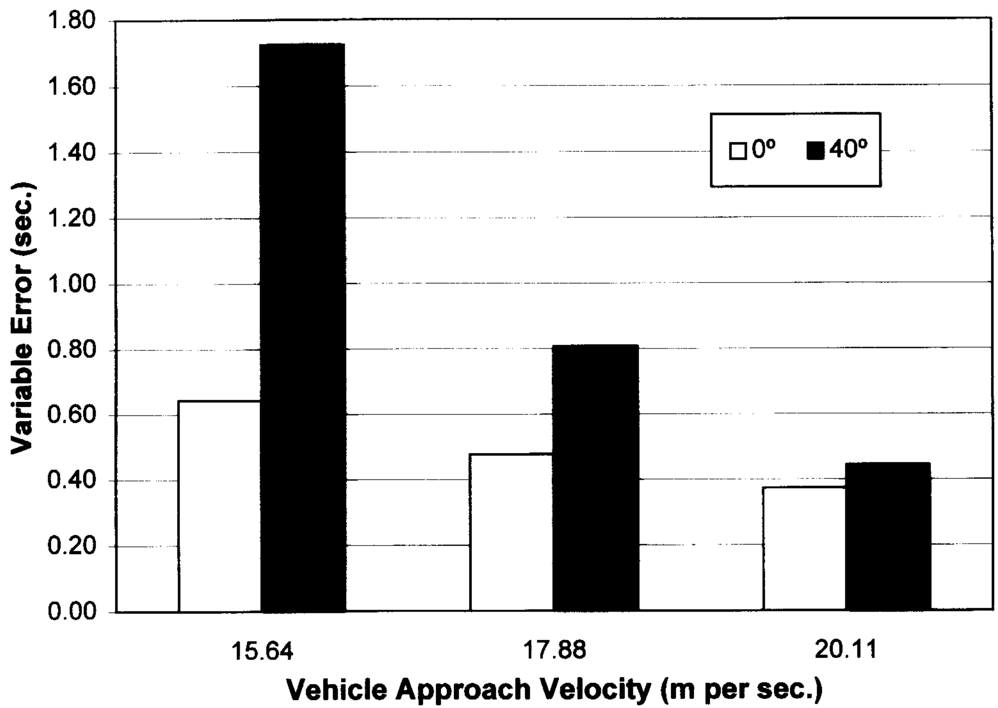

FIGURE 10 Vehicle Approach Trajectory × Vehicle Approach Velocity interaction for variable error. The interaction is a result of a decrease in the variability of T_c estimates as the velocity of the approaching vehicle was increased for the 40° trajectory.

Sex differences. As the results from Experiment 2 indicate, there are systematic and significant differences between male and female ability to estimate T_c contingent on the velocity of an approaching object. Specifically, when the velocity of the approaching vehicle is low, and in this experiment the duration of the trial is relatively high, female estimates of T_c are less accurate and more varied than male; however, with increases in vehicle approach velocity, the accuracy of and variations in T_c estimates between men and women become similar. These results are consistent with previous experiments (Caird & Hancock, 1994; McLeod & Ross, 1983; Schiff & Oldak, 1990) indicating that overall, participant sex and object approach velocity are not mutually exclusive factors, but rather act in a synergistic manner affecting participants' ability to estimate T_c.

Individual differences. As in Experiment 1, for both vehicle approach trajectories there was a tendency to underestimate actual T_c. In addition, there was a tendency for estimates of T_c to become increasingly varied as the velocity of the approaching vehicle was decreased. It must be emphasized that, as with rate of underestimations observed in Experiment 1, a closer examination of the results is necessary to gain a more complete indication of the what actually is occurring in participant responses. More specifically, 449 of the 1,200 responses observed (37%) in Experiment 2 were overestimates of the actual T_c. When paired with the number of overestimates examined in Experiment 1 (22%), it is apparent that a substantial number of responses are overestimates; however, the degree of underestimates skews the results, leading readers to conclude that nearly all estimates of T_c erred on the side of safety. A closer examination of the data reveals that 10% of the participants overestimated actual T_c 80% of the time or more, 20% of the participants overestimated actual T_c 60% of the time or more, 40% of the participants overestimated actual T_c 40% of the time or more, and 75% of the participants overestimated actual T_c 20% of the time or more. Further, it is interesting that when average deviation for each participant is examined (see Figure 11), 14 participants underestimated actual T_c, whereas only 6 participants overestimated actual T_c. Two of those six participants overestimated actual T_c by nearly a full second. When paired with similar information from Experiment 1, this information indicates that of the 40 participants involved in Experiments 1 and 2, at least 6 (15%) would be at greater risk for an accident due to their inability to estimate accurately T_c.

GENERAL DISCUSSION

In these two experiments and previous T_c literature, the inability to estimate T_c accurately and with little variability across and within sexes is symptomatic of a greater entity influencing time estimations. Several tentative interpretations have been forwarded, attempting to elucidate the reasons for these inaccuracies (typically underestimations) and the differences present between male and female estimates

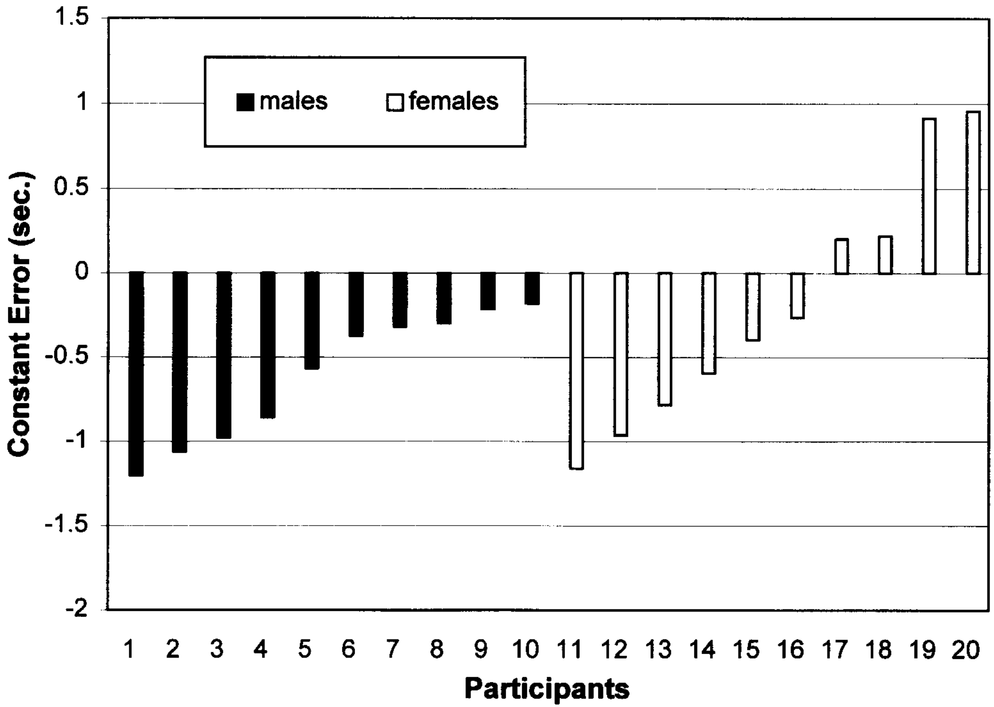

FIGURE 11 Constant error mean for each participant in Experiment 2. Note that the order of participants on the figure does not reflect the order in which participants performed the experiment.

of T_c. McLeod and Ross (1983) suggest differences between male and female estimates of T_c may be due to any one of several explanations. These potential explanations include that men perform better than women on visual acuity tests, men may have more driving experience, and men may be willing to take greater risks than women. However, McLeod and Ross indicated that because of differences in ability and in criteria, they could not determine which explanation has the most potential. Schiff and Oldak (1990) suggested that differences between male and female estimates of T_c may be due to the desire to err on the side of safety rather than risk a dangerous situation. They suggest the root of this desire is because there is a "somewhat inaccurate system" and that the inaccurate system for women resides in their spatial abilities. In examining time-to-passage phenomena, Kaiser and Mowafy (1993) indicated that participants in their experiment also tended to underestimate longer time-to-passage intervals. They suggest the response errors observed in their work could be a result of the cognitive extrapolations observers may have been performing or due to a "distortion" of the visual/temporal space. Stoffregen and Riccio (1990) suggested the reason for misestimates of T_c in their study (also underestimations) is due to the participants responding in a way to keep from getting "hit." All of these propositions sound tenable; however, as indicated by McLeod and Ross (1983), other factors may have an influence on T_c estimates. Tresilian (1995) pointed out that there are indications that an internal timing mechanism exists that measures the amount of time since the approaching object has disappeared. This internal timing mechanism, an "internal clock," may be one of the factors that influence T_c estimates. Specifically, the response bias exhibited by people estimating when an object will reach a particular space–time junction may be due to the operation, or more appropriately the misoperation of the internal clock. Indeed, evidence indicates that there are differences in men's and women's abilities to produce or reproduce intervals of time and that there is a large amount of variation inherent in these tasks (Hancock,1994). It is easy to see that if there is inherent variability in the operation of the internal clock, then any task relying partly or fully on the internal clock also will exhibit variability. Note that one line of research in an allied field has suggested that there may be one central timing mechanism and one or more peripheral timing mechanisms that access the central timing mechanism (Treisman, Cook, Naish, & MacCrone, 1994) to perform tasks accurately. Perhaps there is a peripheral timing mechanism in the human retina that possesses an inherent timing variability (error), affecting T_c estimates. Indeed, there may be multiple peripheral timing mechanisms located in the human retina. The differences in a person's ability to estimate T_c when the vehicle is approaching from a 0° or a 40° trajectory actually may be due to the variability of a particular clocking mechanism in an area of the human retina. We, of course, offer this theory as speculation only and invite other researchers to help us provide evidence for its truth.

As suggested earlier, the research paradigm employed to answer questions obviously influences the answers obtained. Earlier we alluded to inherent limitations to the collision–avoidance paradigm; however, there also are limitations to the removal paradigm. One such limitation concerns the way in which the vehicle is removed from the environment. In normal driving, vehicles do not instantaneously disappear; however, valuable information regarding the functional capacity and limitations of the perceptual system can be gained by employing this paradigm. For example, when an approaching vehicle is occluded by shrubbery, parked vehicles, or other objects, the only T_c information available is the time from initial sighting of the approaching vehicle to the time when it becomes occluded. It is in this short time that a person must use the visually specified T_c information to determine if and when the approaching object will collide. Therefore, it is possible that occlusion of the object and removal of the object have differing influences upon T_c estimates (Kaptein, 1994). This is an important difference, because if the visual information is equated between removal and occlusion, some other influence must operate for estimates to vary. Initial observations in our current work and observations of others confirm this possibility.

A limitation to most T_c experiments is a lack of visual realism and generalizability. *Realism* is the degree to which the simulation or testing environment represents or reflects the real world (Kantowitz, 1992), whereas *generalizability* is the ability to extend the results obtained through tests to other populations and environments (Chapanis, 1988). Kantowitz (1992) suggested that the ability to generalize results is not a byproduct of increased realism, but rather from similarity of psychological processes between the testing environment and the goal environment. Providing further support for this, Schiff and Arnone (1995) suggested identifying processes and environments typically manipulated and inherent in normal driving situations and using these processes and environments in simulations used to examine driving behavior. However, the most salient processes in a real driving environment have yet to be unequivocally established. In this study, we have taken a number of steps toward this goal. The first step is the use of high resolution graphics that facilitate the reality of the scene. These graphics allowed the participant to see logos on vehicles, oil stains on the streets, and individual branches and leaves on trees. The second step taken in the present work to enhance realism and generalizability was to project the vehicles on a display surface with real life size. For example, in a real driving situation, a Porsche 911 subtends a vertical visual angle of .94°, 80.46 m from an observer, whereas in our first experiment, the simulated Porsche 911 subtended a vertical visual angle of 1.29° a distance of 80.46 m. Depicting vehicles as close to real-life size as possible may improve the cognitive similarities between the simulated world and the real world.

However, what do such statistical and individual differences mean with respect to such real-world concerns as accident involvement? The implicit reasoning of this work and related experiments (e.g., Caird & Hancock, 1994) is that fuller understanding of phenomena involved in T_c estimates will reveal important insights into collision events such as those involved in specific maneuvers like left turns. But is this assumption viable? Unfortunately, understanding the antecedents of accidents is not that simple. Accidents are rare events. They are nonlinear occurrences embedded in a nominally linear world. They frequently involve the interaction of multiple adaptive agents and as the confluence of multiple causation, they defy simplistic elucidation (Hancock, 1995). Therefore, the equation of potential accident involvement with the *average* overestimations of T_c is a potentially misleading assertion. At best, the identification of such individuals with a possible propensity for T_c errors in the real world is a tentative first step. Whether such individuals are aware of this propensity and self-regulate behavior with such ability is, at present, unknown. What is clear is that there are specific driving maneuvers in which classic T_c information provides the major cues for response. Inability or deterioration of such capability cannot, therefore, be a trivial factor in accidents.

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