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Time-To-Contact: More Than Tau Alone

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Two *time-to-contact* (T_c) experiments are reported that manipulated the manner in which a visually simulated target vehicle disappeared from the screen. In both experiments, one condition featured the traditional, spontaneous disappearance of the vehicle. A contrasting condition featured the occlusion of the vehicle behind a natural object. The available visual information was essentially equivalent in each condition. If T_c is specified by information in the expanding optic array alone, the two conditions should produce equivalent estimates of T_c. Results of each experiment, however, showed estimates with 14% and 12% greater accuracy in the occlusion condition compared to the disappearance condition. This implies that T_c judgments depend on more than the rate of optical expansion. In addition to the occlusion manipulation, factors influencing the accuracy of T_c estimates included both the sex and age of the participant. In an effort to compare T_c estimates with time-judgment ability, participants also performed a time-production task with the same temporal structure as the T_c task but with no graphic scene representation. A positive relation was found but further clarification is still needed between these two capabilities.

The ability to know when an approaching object will reach oneself in space is a critical skill for surviving in any environment. A practical need for this skill occurs every time a motorist crosses an unregulated intersection. To be successful, the driver must determine when approaching vehicles will reach his or her position and guide actions based on this information. Failure in any part of this process may well lead to an accident (Hancock, 1998a).

In previous work (Hancock & Manser, 1997), we reviewed much of the work on *time-to-contact* (T_c; noting all of the terminological variants we were aware of), underscoring the persistent underestimations of T_c judgments in the literature (cf. Figure 1 in Manser & Hancock, 1996). In that article, we were critical of the

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frequently used "removal" paradigm in T_c research but did not focus that research on it.

In the removal situation, a portion of an approach is specified to an observer, a portion that is mathematically sufficient to specify T_c, and observers are then asked to judge when the approaching surface actually would have made contact with them. In such studies, whatever was visually simulated to be approaching ceased to be visible and the task was one of extrapolating the seen motion. From an ecological viewpoint, the manner in which something ceases to be visible is very important (e.g., Gibson, 1950; 1961; 1968; 1979/1986, chapters 11 & 14; Gibson, Kaplan, Reynolds, & Wheeler, 1969). When a target simply disappears from a display, no clearly specified event happened except something like film editing (Stoffregen, 1997). It is not shown to explode or vaporize. The most common way for something to go out of view in a cluttered environment is by *occlusion*, in which the texture of one opaque object hides another. However, little attention has been paid to the role of the manner of disappearance in describing the research on time-to-collision. The studies reported in this article directly compare T_c judgments in which an approaching vehicle simply disappears with those in which an approaching vehicle is occluded.

Several other factors that have been implicated in T_c performance are investigated here. First, it has been observed that T_c estimates are influenced by the velocity of the approaching vehicle. In particular, it has been shown consistently that observers' T_c estimates are more accurate when the object is approaching at higher velocities (Caird & Hancock, 1994; Manser & Hancock, 1996; Schiff, Oldak, & Shah, 1992). Caird and Hancock, Manser and Hancock, and Schiff and Oldak (1990) showed that men estimate T_c more accurately than women (for an exception, see Schiff et al., 1992). Manser and Hancock suggested that the sex difference in estimating T_c may be partly contingent on the velocity of the approaching object. In a study that found few sex differences, Schiff et al. used simulated vehicle approach velocities of only 10 and 20 mph, whereas Caird and Hancock, Manser and Hancock, and Schiff and Oldak, all of which found significant sex differences, used a much wider range of simulated vehicle approach velocities.

A second factor that appears to influence T_c estimates is age. Schiff et al. (1992) found significant differences between young observers' (20–45 years of age) and older observers' (65–83 years of age) T_c estimates. They pointed out that the effect for age resides mainly in the decreased accuracy of older women's estimates of T_c and not in the overall ability of older observers for estimating T_c. In addition, using four age groups (5–6, 7–8, 9–10, and 18–54 years of age) Hoffmann (1994) examined observers' abilities to estimate time-to-arrival and found differences across the age groups.

To address the systematic underestimations and inherently large variability in estimates of T_c, several researchers (e.g., Schiff & Oldak, 1990) suggested that humans have a tendency to underestimate T_c to buy additional time to react to avoid potentially harmful contact (see also Schiff et al., 1992). They speculated that women's T_c estimates were more cautious (greater underestimation) than men's because women have less confidence in their perceptual–motor response ability and as a consequence need additional time to reevaluate a potentially dangerous situation. Another suggested explanation for the inaccuracy in T_c estimates comes from the inherent variability of an internal time-keeping process subserving the ability to estimate T_c (Tresilian, 1995).

RESEARCH SCENARIO

In this study, we address the question of observer inaccuracy in T_c estimates. Specifically, the purpose of this study is to determine if differences exist in the ability to estimate T_c contingent on the method by which the approaching vehicle is removed from the visual display. If observers' estimates of T_c are more accurate in the occlusion condition compared with the traditional *removal* condition, it would undermine the *safety* explanation of the usual underestimates because the tau information is identical in the two cases. We also wish to evaluate the impact of observer age, sex, and vehicle approach velocity on these respective methodological procedures. Finally, we wish to compare T_c estimation with raw time estimation ability in situations that are strictly comparable to one another.

EXPERIMENT 1

Experimental Method

Experimental Participants

The participants in this study (N = 40) were 10 men and 10 women between 18 and 30 (m = 22.95, range 19–29) years of age and 10 men and 10 women between the ages of 55 and 70 (m = 61.20, range 55–68). Participants were recruited from the faculty, staff, and student body of the University of Minnesota and from local churches, retirement communities, and senior citizen organizations throughout Minnesota and northwestern Wisconsin. They received no money or class credit for their participation. All participants possessed a valid Minnesota or Wisconsin driver's license, had 20/20 vision or corrected to 20/20 vision via contact lenses or glasses, and possessed no known physical or cognitive limitations that might have affected their performance in this study.

Experimental Apparatus

This study was conducted in a high-fidelity wrap-around environment simulator, Figure 1. The simulator consisted of a spherical steel and wooden dome structure onto which eight white fiberglass screens were fixed. Each screen extended up from the floor and was 250 cm in height. Each screen was meshed with the adjacent

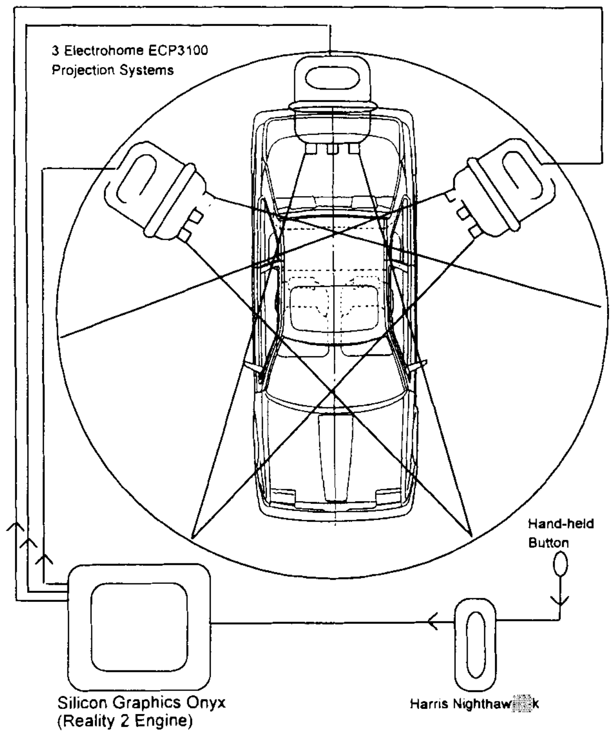

FIGURE 1 Top-down schematic of the University of Minnesota Human Factors Research Laboratory wrap-around simulation facility.

screens so it appeared as if there were a single screen wrapping around the driver and vehicle. At the widest point the wrap-around screen created a diameter of 549 cm, 22 cm above the floor whereas the diameter at floor level was 472 cm. The driving scene presented to participants was created by Coryphaeus Easy Scene® computer software, generated by a Silicon Graphics Incorporated® Onyx computer (Reality2 engine), and projected through three Electrohome ECP–3100® projectors to the curved wall of the simulator. The three separate images projected to the curved wall were arranged to appear as one single image subtending a 165° field of view horizontally and a 55° field of view vertically. Participants sat in the driver's seat of a full-sized 1985 Acura Integra RS, which was positioned in the center of the simulator. Participant responses were collected via a Nighthawk® 4402 data collection computer connected to a hand-held button switch.

Experimental Procedures

Participants read and signed a Human Subjects Consent form prior to beginning the study. They were then seated in the driver's seat of the Acura Integra and were given the hand-held button. Participants received general onscreen instructions regarding the experiment and were then presented with either a time-production task or a T_c task. The presentation order of these tasks was counterbalanced across age and sex.

The time-production portion of the experiment required participants to perform a total of 40 trials, each trial consisted of several steps. When participants performed the time-production portion of the experiment they first viewed onscreen instructions. Then participants viewed a numeral specifying the time they would be asked to produce after a visual stimulus (a yellow sphere) had disappeared. Shortly after the requested time-interval number was removed from the screen the yellow sphere was presented to the participant at eye level. The yellow sphere subtended a visual angle of 9.22°. The sphere remained on the screen for 14.21 sec and then disappeared. This time corresponded to convenient velocities simulated in the T_c task. The participant's task was to wait for the requested time interval after the visual stimulus had disappeared and then to press the hand-held button. After pressing the hand-held button the trial was complete and the next trial was presented. Participants were asked to produce an arbitrary time interval of 9.58 sec for the first 10 trials and were provided with feedback in numerical form regarding their performance after the completion of each trial. These trials served as practice for the participants and also served as a baseline time-frame reference for all participants. Participants then performed 10 trials in each of three requested time intervals. Like the practice trials, the visual stimulus remained on the screen for 14.21 sec and then disappeared, but the participant was asked to produce time intervals of either 1.95, 2.19, or 2.49 sec after the visual stimulus disappeared and were not provided with feedback about their performance. All 30 trials were randomly assigned to each participant.

For the T_c portion of the experiment, each participant viewed onscreen instructions. After pressing the hand-held button a computer-generated driving scenario was presented. This consisted of a standard unregulated four-way intersection with each road being designed for contralateral traffic flow. The driving scenario showed that the viewer was positioned slightly into the intersection waiting to make a left turn. For all experimental trials a white vehicle (a Lotus Esprit) appeared on the scene, simulated to be traveling at a constant velocity of either 45 mph (20.11 m/sec), 40 mph (17.88 m/sec), or 35 mph (15.64 m/sec). In the occlusion condition, the Lotus Esprit disappeared behind a bush on the side of the road 39 m before collision. In the contrasting condition, the approaching Lotus Esprit merely vanished 39 m before collision. While the approaching vehicle was visible, it appeared on a collision course for the participant, and in all six conditions it remained visible for 14.21 sec and disappeared from view at either 1.95, 2.19, or 2.49 sec before collision with the viewer's vehicle. Figure 2 depicts the driving scenario.

The 1.95-, 2.19-, and the 2.49-sec T_c correspond to the 45-, 40-, and 35-mph vehicle-approach-velocity conditions, respectively. In an effort to control for possible confounds because of relative size effects (DeLucia, 1991) we chose to either remove or occlude the approaching vehicle at identical positions, thus determining

FIGURE 2 A depiction of the driving scenario. Note, this is not a true representation of the driving scene due to the inherent limitations representing a three-dimensional scene in a two-dimensional picture.

identical final positions for the approaching vehicle for all experimental trials. However, manipulating the velocity at which a vehicle approached the participants (15.67, 17.88, and 20.11 m/sec) and controlling the final position of the approaching vehicles would have effectively created three separate viewing times. To effectively control for viewing time (shown to be important in Caird & Hancock, 1994; Manser & Hancock, 1996), we decided to have the vehicle appear in the scenario at three separate simulated distances from the viewer and disappear or become occluded at one distance (39 m) from the participant. These appearance distances were either 325.00, 293.10, or 261.34 m from the participant's location for the 45-, 40-, or 35-mph vehicle-approach-velocity conditions, respectively. The end result was that participants viewed the approaching car in all conditions for equal periods of time (14.21 sec), viewed identical final vehicle positions, and viewed the same maximal subtended viewing angles in all conditions.

Experiments performed in the area of T_c estimations have indicated that participants have a tendency to estimate T_c more accurately when they are able to see the vehicle for greater distances (Caird & Hancock, 1994). The variables of viewing time, viewing distance, and vehicle approach velocity are interconnected in that one variable cannot be altered without altering at least one of the others. We held viewing time and vehicle approach velocity constant and permitted viewing distance to "float" because the expansion rate of the image of the approaching vehicle on the retina at the end of the vehicle's approach would be more salient than the expansion rate of the image of the approaching vehicle at the beginning of the vehicle's approach. It was the participants' task and goal in this experiment to press the hand-held button when they felt the approaching vehicle would have reached their position had it not become occluded or disappeared from the driving environment. Participants performed 10 experimental trials in each of the six separate experimental conditions. All 60 trials were presented randomly to each participant. Participants were provided with three practice trials before performing the experimental trials. The first practice trial depicted the Lotus Esprit appearing 293.1 m from the participant traveling the entire distance to the participant at a constant velocity of 40 mph. A practice trial in which the approaching vehicle traveled the entire distance to the participant was included here because anecdotal indications provided by participants in previous driving simulation research in our research laboratory indicated difficulties judging T_c when the final position and size of the approaching vehicle at collision were seen for the first time. The second practice trial was identical to the first experimental trial except the approaching vehicle was occluded by a bush placed on the side of the road. The third practice trial was identical to the first and second experimental trials except the vehicle simply disappeared from the scene at the same position as in the occlusion case. The second and third practice trials were included to show participants what would occur during the research-scenario test trials. As in the practice trials, the participants were to press the hand-held button when they felt the approaching vehicle would have collided with their vehicle. The independent variables were the type of research scenario used, the age of the participant, the sex of the participant, and the velocity of the approaching vehicle. The dependent measure was the estimated T_c of the approaching vehicle.

Several similarities between the time-production portion and the research-scenario portion of the experiment should be apparent at this point. Specifically, the amount of time that participants saw the visual stimulus was identical in both the time-production and the research-scenario portions of the experiment (14.21 sec). The requested time-production intervals and actual T_c in both experiments also were identical (1.95, 2.19, and 2.49 sec). In both situations a stimulus was presented by the computer program, an unfilled (with respect to the experimental manipulations) time period was then experienced by the participant, and then the participant responded to complete the trial. For each condition in the time-production and research-scenario portions of the experiment, 10 experimental trials were performed. The parallel conditions allowed us to examine the relation between T_c and time production.

Experimental Design

Time-production examination. In addition to examining estimates of time production, several derived dependent variables were examined. The derived dependent variables were response bias (constant error), overall accuracy in performance (absolute error), and response consistency (variable error) of time-production estimates (for error deviations, see Schmidt, 1988). The time-production estimates and the derived dependent variables were analyzed using a 2 × 2 × 3 (Sex × Age Group × Time-Production Interval) mixed analysis of variance (ANOVA) with sex and age group (young and old) as between-subject variables and time-production interval (1.95, 2.19, or 2.49 sec) as a within-subject variable. The alpha level was set at .05 and significant differences were distinguished using Tukey's HSD post hoc test.

Research-scenario examination. In addition to examining actual T_c estimates several derived dependent variables were examined. The derived dependent variables were, again, response bias (constant error), overall accuracy in performance (absolute error), and response consistency (variable error). The actual T_c scores and the derived dependent variables were analyzed in a 2 × 2 × 2 × 3 (Age Group × Sex × Research Scenario × Vehicle Approach Velocity) mixed ANOVA with age group (young vs. old) and sex (male vs. female) as between-subject variables and research scenario (removal versus occlusion) and vehicle approach velocity (45, 40, or 35 mph) as within-subject variables. The alpha level was set at .05 and significant differences were distinguished using Tukey's HSD post hoc test.

T_c and time production correlation. To determine the strength of the relation between T_c and time-production estimates, a Pearson product moment correlation was performed on the actual T_c and time-production estimates at each of the three time intervals (1.95, 2.21, and 2.49 sec).

Experimental Results

The data analyses for one woman in the older age group were omitted in all statistical analyses because her mean scores for T_c estimates were more than three standard deviations from the mean score of all participants.

Time Production

Time estimates. There was a main effect for time-production interval, $F(2, 70) = 39.65, p < .01$. Post hoc analysis indicated that the 2.49 sec time-production interval was significantly different from the 2.19 and the 1.95 sec time-production intervals, respectively. The means for the 2.49, 2.19, and 1.95 sec time-production intervals were 4.49, 3.26, and 1.97 sec, respectively. No other main effect or interaction were present in the actual time estimates.

Constant error analysis. There was a main effect for time-production interval in the constant error analysis, $F(2, 70) = 24.44, p < .01$. Post hoc analysis indicated each time-production interval (2.49, 2.19, and 1.95 sec) was significantly different from each other time-production interval. The means for the 2.49, 2.19, and 1.95 sec time-production intervals were 2.00, 1.07, and .02 sec, respectively. No other main effects or interactions were present in the constant error analysis.

Absolute error analysis. There was a main effect for time-production interval for the absolute error analysis, $F(2, 70) = 18.22$, $p < .01$. Post hoc analysis indicated the 2.49 sec time-production interval was significantly different from the 2.19 and the 1.95 sec time-production intervals. The means for the 2.49, 2.19, and 1.95 sec time-production intervals were 2.34, 1.35, and .76 sec, respectively. No other main effects or interactions were present in the absolute error analysis.

Variable error analysis. No main effects or interactions were present in the variable error analysis for time production.

Research-Scenario Examination

T_c analysis. The analysis conducted on the T_c estimates revealed a main effect for research scenario, a main effect for vehicle approach velocity, and an Age × Vehicle Approach Velocity interaction. Results of the main effect for research scenario, $F(1, 35) = 9.77$, $p < .01$, indicated that participants estimated T_c more accurately when the approaching vehicle was occluded by the bush. As can be seen from Figure 3, participants were 14% more accurate determining T_c when the approaching vehicle disappeared from view by occlusion. There was a main effect for vehicle approach velocity, $F(2, 70) = 35.4$, $p < .01$. The means for the 35-, 40-, and 45-mph vehicle approach velocities were 2.00, 1.78, 1.71 sec (80%, 81.3%, and 87.7% of actual T_c), respectively. Tukey's post hoc analysis indicated the 35-mph vehicle approach velocity was significantly different from both the 40- and 45-mph vehicle approach velocities. The main effect for vehicle approach velocity is in direct agreement with previous findings indicating that participants are more accurate estimating T_c when the vehicle approach velocity is higher (Manser & Hancock, 1996). The main effect for vehicle approach velocity can be seen in Figure 3 as a function of research scenario.

The Age × Vehicle Approach Velocity interaction, $F(2, 70) = 4.09$, $p < .05$, indicated that when the approaching vehicle traveled at progressively higher velocities, the accuracy of T_c estimates increased for both age groups, but the differences between the younger participants' and older participants' scores also increased (see Figure 4). When these scores were converted to a percentage of actual T_c it can be seen that the difference between younger and older participants' estimates of T_c at the 35-mph vehicle approach velocity was only 7%, whereas the difference between the T_c estimates increases to 11% at the 45-mph vehicle approach velocity. No other main effects or interactions were significant for the analysis on actual T_c scores.

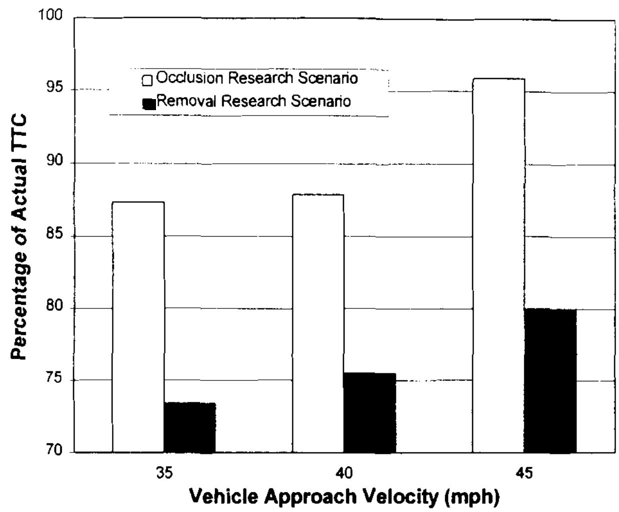

FIGURE 3 The main effect for research scenario and the main effect for vehicle approach velocity expressed as a function of each other. Estimated time-to-contact (T_c) scores have been converted to a percentage of T_c for comparative ease.

Constant error analysis. The constant error analysis revealed a main effect for research scenario, a main effect for vehicle approach velocity, a Research Scenario × Vehicle Approach Velocity interaction, and an Age × Vehicle Approach Velocity interaction. The main effect for research scenario, $F(1, 35) = 9.77$, $p < .01$, revealed that when participants viewed the occlusion research scenario T_c estimates were underestimated significantly less than when participants viewed the removal research scenario. However, it should be noted that participants underestimated T_c for both the occlusion and the removal research scenarios. Constant error means for the occlusion and removal research scenarios were –.22 and –.53, respectively. The main effect for vehicle approach velocity, $F(2, 70) = 5.49$, $p < .01$, indicated that T_c estimates were underestimated for all three vehicle approach velocities, but T_c estimates were progressively more accurate as the vehicle approached at progressively higher velocities. Post hoc analysis indicated the 35-mph vehicle approach velocity was significantly different from the 45-mph vehicle approach velocity. There was a Research Scenario × Vehicle Approach Velocity interaction for constant error, $F(2, 70) = 29.86$, $p < .01$. The interaction is a result of the substantial decrease in the bias of T_c estimates for the occlusion research scenario when the vehicle traveled at the highest velocity (20.11 m/sec). In comparison, T_c estimates for the removal scenario decreased in a nearly linear manner as the vehicle approach velocity increased progressively. Figure 5 depicts this interaction.

The Age × Vehicle Approach Velocity interaction, $F(2, 70) = 4.09$, $p < .01$, indicated that as the vehicle approach velocity increased progressively, T_c estimates for young participants became progressively less biased. T_c estimates for older participants also became less biased as the vehicle approach velocity increased progressively, but the benefits were not evident until the vehicle approached at 45 mph. This interaction is shown in Figure 6. No other main significant main effects or interactions were found in constant error.

Absolute error analysis. Results for the absolute error analysis revealed a main effect for research scenario and a Research Scenario × Vehicle Approach Velocity interaction. The main effect for research scenario, $F(1, 35) = 4.61, p < .05$, indicated a smaller absolute error for T_c estimates when the approaching vehicle was occluded versus disappearing en route. Means for the absolute error for the occlusion and removal research scenarios were .77 and .92 sec, respectively. The interaction between research scenario and vehicle approach velocity, $F(2, 70) = 3.53, p < .05$, indicated that participants' T_c estimates contained smaller errors and were more stable across the three vehicle approach velocities for the occlusion research scenario than T_c estimates for the removal research scenario. Specifically, absolute error scores for the removal research scenario ranged from .99 to .86 to .92 sec for the 35-, 40-, and 45-mph vehicle approach velocities as opposed to the absolute error scores for the occlusion research scenario with means of .81, .77, and .75 sec. This interaction is depicted in Figure 7.

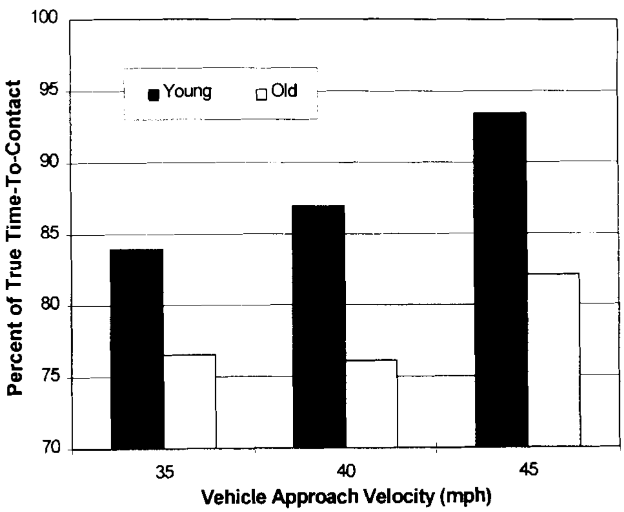

FIGURE 4 The Age × Vehicle Approach Velocity interaction for actual time-to-contact (T_c) scores. The estimated T_c scores have been converted to a percentage of actual T_c for ease of comparison. The interaction results from the clear increase in the accuracy of T_c estimates for the young participants as compared to the marginal increase in the accuracy of T_c estimates for the older participants.

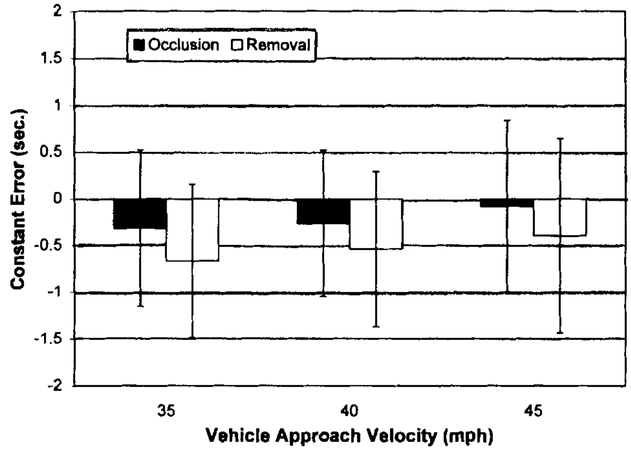

FIGURE 5 The Research Scenario × Vehicle Approach Velocity interaction for constant error. As vehicle velocity increases, estimates of bias diminish for both the removal and occlusion research scenarios. However, there is a substantial decrease in the bias of time-to-contact estimates at higher vehicle approach velocities for the occlusion research scenario.

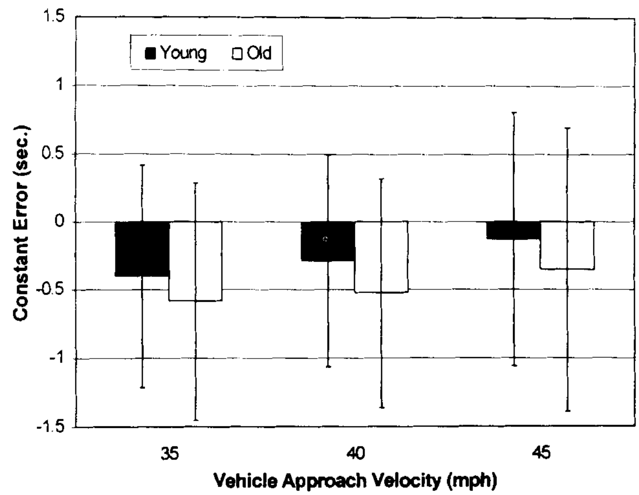

FIGURE 6 The Age × Vehicle Approach Velocity interaction for constant error. The interaction indicates that both age groups perform with progressively less bias as vehicle approach velocity increases, but the difference between the age groups maximize at 40 mph and then become dissimilar at 45 mph.

Variable error analysis. No main effects or interactions were present in the variable error analysis.

Correlation Between T_c and Time-Production Estimates

The Pearson product moment correlations between T_c estimates and time-production scores for each time interval were –.54, –.46, and –.35 for the 1.95, 2.19, and 2.49 sec time intervals, respectively. The correlations across time intervals indicates that as time interval increases the T_c and time-production estimates progressively diverge (see Figure 8).

Summary of Results

Overall, the results of this experiment indicated that participants estimated T_c with greater accuracy and with less bias when the approaching vehicle was occluded as opposed to disappearing. Results confirmed previous findings that as the velocity of the approaching vehicle increased, estimates of T_c were more accurate and contained less bias. When research scenario and vehicle velocity were examined it was found that T_c estimates for the occlusion and removal scenario tended to converge with increased vehicle approach velocity. However, it should be recalled that at the highest vehicle approach velocity there still existed significant differences between the two research scenarios. In general, younger participants produced T_c estimates that were more accurate than those of their older counterparts, but interactive effects exist when vehicle

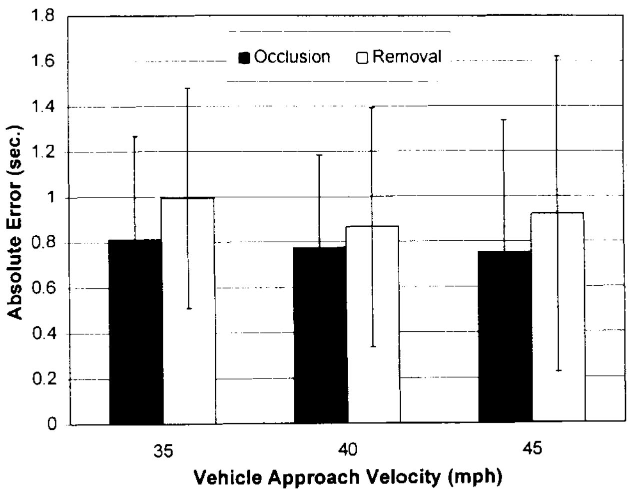

FIGURE 7 The Research Scenario × Vehicle Approach Velocity interaction for absolute error. As vehicle velocity increases, the accuracy of estimates increases for both the removal and occlusion research scenarios. However, there is a progressive increase in accuracy for the occlusion research scenario, which is not reflected in the scores for the removal research scenario.

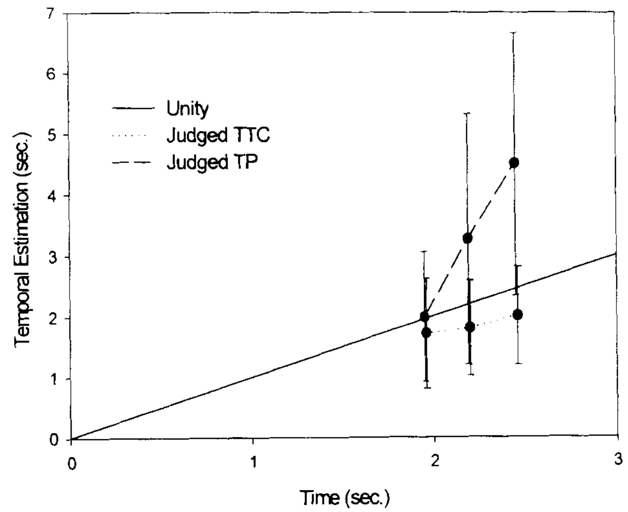

FIGURE 8 The means and standard deviations for time-to-contact (T_c) and time-production estimates for each time interval. Note that T_c is progressively underestimated whereas time production is consistently overestimated.

approach velocity was examined in conjunction with participant age group. Results of the time-production analysis indicated participants overestimated time production, and such overestimations increased progressively with increased time-production intervals. Lastly, there was a strong, but negative, correlation between T_c and time-production estimates.

EXPERIMENT 2

The purpose of the second experiment was to extend Experiment 1 to include a wider and more representative range of kinematic conditions. A subsidiary consideration was to determine if the lack of sex differences in Experiment 1 could be attributed to the limited range of T_c chosen in that procedure. Previous studies, which have reported sex differences in T_c, have used vehicle approach velocities and viewing times well in excess of those employed in Experiment 1 (Caird & Hancock, 1994; Manser & Hancock, 1996; Schiff & Oldak, 1990). In addition to the restricted range of vehicle approach velocities, the lack of significant sex differences might have been because of low absolute T_c values. In response to these concerns, the range of vehicle approach velocities and the absolute values of T_c were increased.

Experimental Method

Experimental Participants

There were 24 participants in this study, 6 men and 6 women between 18 and 27 (m = 22.6, range 18–27) years of age and 6 men and 6 women between the ages of 55 and 83 ($m = 70.6$, range 55–83). Participants were recruited according to the criteria and characteristics set forth for in Experiment 1.

Experimental Apparatus

The experimental apparatus used in Experiment 2 was identical to that in Experiment 1.

Experimental Procedures

The experimental procedures used in Experiment 2 were identical with those in Experiment 1, except for the modification of the time-production and T_c time intervals and the occluder presented to participants in the driving scenario. Time intervals of 1, 3, 5, and 7 sec were used for both the time-production and T_c tasks. The vehicle disappeared or was occluded at a constant simulated distance of 66 ft before collision with the participant's vehicle. To facilitate the ecological validity of the driving scenario, a row of shrubs as illustrated in Figure 9 replaced the single tree used in Experiment 1.

Experimental Design

Time-production examination. Actual estimates of time production, constant error, absolute error, and variable error of time-production estimates were

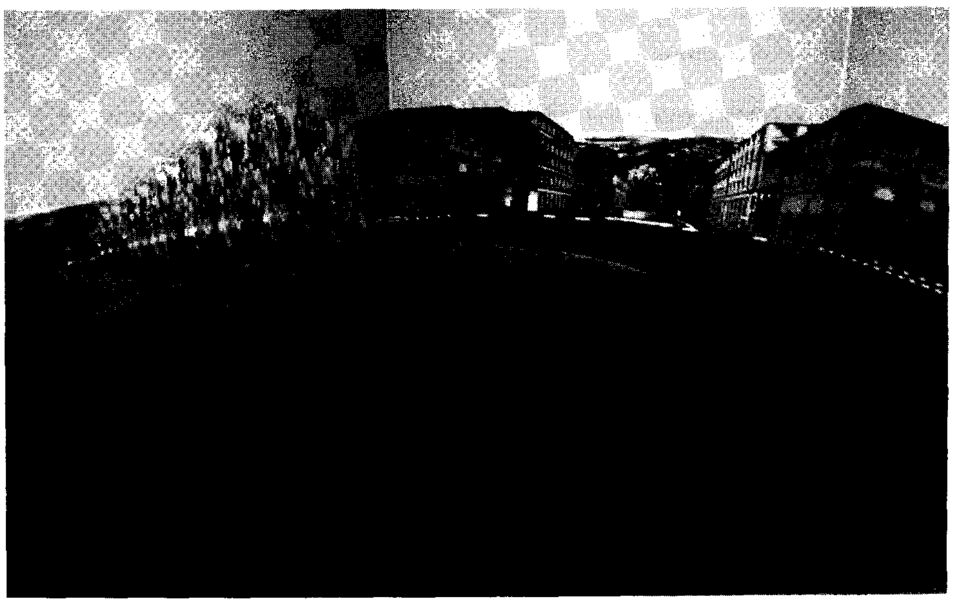

FIGURE 9 A depiction of the computer-generated driving scenario for the occlusion research scenario for Experiment 2. Note, the scenario appears to be distorted due to inherent difficulties reproducing three-dimensional images in a two-dimensional plane.

examined. The actual time-production estimates and the derived dependent variables were analyzed in a 2 × 2 × 4 (Age × Sex × Time-Production Interval) mixed ANOVA with age (younger vs. older) and sex (male vs. female) as the between-subject variables and time-production interval (1, 3, 5, or 7 sec) as the within-subjects variables. The alpha level was set at .05, and significant differences were distinguished using Tukey's HSD post hoc test.

Research-scenario examination. Actual estimates of T_c and the derived dependent variables of constant error, absolute error, and variable error were examined. The actual T_c scores and the derived dependent variables were analyzed in a 2 × 2 × 2 × 4 (Age × Sex × Research Scenario × Vehicle Approach Velocity) mixed ANOVA with sex (male vs. female) and age (younger vs. older) as between-subject variables and research scenario (removal vs. occlusion) and vehicle approach velocity (6, 9, 15, and 44 mph) as within-subjects variables. The alpha level was set at .05, and significant differences were distinguished using Turkey's HSD post hoc test.

Relation between T_c and time production. To determine the strength of the relation between T_c and time-production estimates, a Pearson product moment correlation was performed on the T_c estimates and time-production estimates at each of the four time intervals (1, 3, 5, or 7 sec).

Experimental Results

The data for one woman in the older participant age group and one woman in the younger participant age group were omitted from all T_c and time-production statistical analyses because their mean scores for T_c estimation were more than three standard deviations from the mean score of all other participants.

Time-Production Examination

Time-production estimates. The time-production analysis indicated a main effect for time-production interval, $F(3, 54) = 505.15$, $p < .01$. The means for the 1, 3, 5, and 7 sec time-production intervals were 1.17, 3.11, 5.02, and 7.03 sec, respectively. Post hoc analysis indicated all means were significantly different from each other. When the 1.17-, 3.11-, 5.02-, and 7.03-sec means are converted to a percentage of actual time production (117%, 103.4%, 100.4%, and 100.4%, respectively) it can be seen that time-production estimates became increasingly accurate in both relative and absolute levels as the time-production interval increased. No other main effects or interactions were present in the actual time-production analysis.

Constant error. There were no significant main effects or interactions for the time-production constant error analysis.

Absolute error. There was a main effect for time-production interval in the absolute error analysis, $F(3, 54) = 4.96, p < .01$. The means for the 1, 3, 5, and 7 sec time-production intervals were .41, .66, .72, and .90 sec, respectively. Post hoc analysis indicated that the only significant difference was the 1- and 7-sec comparison.

Variable error. There were no significant main effects or interactions for the time-production variable error analysis.

Research-Scenario Examination

Actual T_c. The analysis conducted on the T_c estimates revealed a significant main effect for research scenario, a main effect for vehicle approach velocity, a main effect for age, and significant interactions between research scenario and vehicle approach velocity. The main effect for research scenario, $F(1, 18) = 8.41, p = .01$, indicated that participants estimated T_c more accurately when the approaching vehicle was occluded by the row of shrubs on the side of the road (mean of 3.33 sec with the goal of 4 sec) as compared with the instantaneous removal of the approaching vehicle (mean of 2.84 sec with the goal of 4 sec). The main effect for research scenario is presented in Figure 10 as a function of vehicle approach velocity. As indicated in Figure 10, participants were 12% more accurate estimating T_c when the approaching vehicle was occluded by the row of shrubs as compared with its instantaneous removal. This percentage increase in accuracy was similar to the 14% change experienced in Experiment 1. There was also a main effect for vehicle approach velocity, $F(3, 54) = 89.96. p < .01$, which indicated that participants' T_c estimates became more accurate with progressive increases in vehicle approach velocity, with the exception of the final condition. The means for the 6-, 9-, 15-, and 44-mph vehicle-approach-velocity conditions were 4.44, 3.91, 2.79, and 1.21 sec, respectively. When these means were converted to a percentage of actual T_c the resulting accuracy percentages were 63, 78, 93, and 120% for the 6-, 9-, 15-, and 44-mph vehicle approach velocities, respectively. Post hoc analysis indicated that only the 44- and the 15-mph vehicle approach velocity were not significantly different from each other. The main effect for velocity is presented in Figure 10 as a function of research scenario. There was a Research Scenario × Vehicle Approach Velocity interaction, $F(3, 54) = 3, p < .01$, which indicated that, although T_c estimates for both research scenarios increased, estimates of T_c also diverged as vehicle approach velocity increased.

The main effect for age, $F(1, 18) = 6.48, p < .05$, indicated that younger participants estimated T_c more accurately at 3.6 sec (goal time was 4 sec) than the older participants, who estimated T_c at 2.57 sec (goal time was 4 sec). When these means were converted to a percentage of actual T_c it was found younger and older participants estimated T_c at 90% and 64% accuracy, respectively. The main effect for age is illustrated in Figure 11 as a function of vehicle approach velocity. The interaction between age and vehicle approach velocity, $F(3, 54) = 5.88, p < .01$,

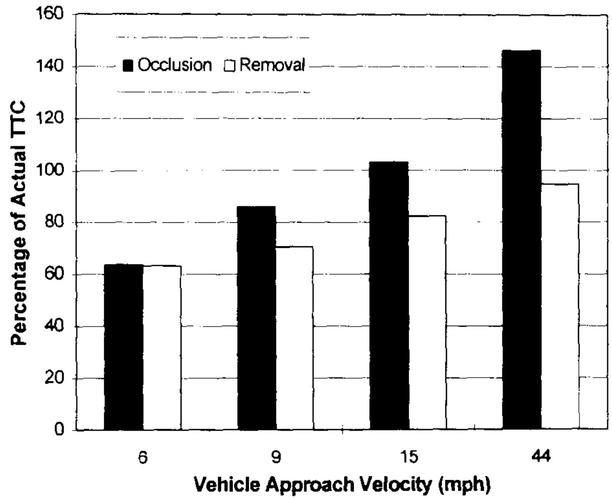

FIGURE 10 The Research Scenario × Vehicle Approach Velocity interaction for the actual time-to-contact (T_c) analysis. Actual scores have been converted to a percentage of actual T_c to facilitate comparison.

indicated that younger participants' estimates of actual T_c were higher than their older counterparts for the 6-, 9-, and 15-mph velocity, but they estimated T_c lower than the older participants at the highest vehicle approach velocity tested. This interaction is displayed in Figure 11. No other main effects or interactions were present in the actual T_c analysis.

Constant error. The constant error analysis revealed a main effect for research scenario, a main effect for vehicle approach velocity, a Research Scenario × Vehicle Approach Velocity interaction, a main effect for age, and an Age × Vehicle Approach Velocity interaction. The main effect for research scenario, $F(1, 18) = 8.41$, $p = .01$, is similar to the results from Experiment 1, indicating that participants' T_c estimates were significantly less biased when the approaching vehicle was occluded by naturally occurring objects as compared to a situation in which the approaching vehicle instantaneously disappeared. The constant error means for the occlusion and removal research scenarios were –.67 and –1.16 sec, respectively. The main effect for research scenario is displayed in Figure 12 as a function of vehicle approach velocity. The main effect for vehicle approach velocity, $F(3, 54) = 67.9$, $p < .01$, indicated that T_c estimates were progressively less biased as the vehicle approach velocity increased. The means for the 6-, 9-, 15-, and 44-mph vehicle approach velocities were –2.56, –1.09, –.21, and .21 sec. Post hoc analysis indicated all vehicle-approach-velocity comparisons were significantly different from each other except the 15- and 44-mph comparison. The main effect for vehicle approach velocity is illustrated in Figure 12 as a function of research scenario. The Research Scenario × Vehicle Approach Velocity interaction for the constant error analysis, $F(3, 54) = 3.00$, $p < .05$, indicated participants estimated T_c with progressively less bias as vehicle approach velocity increased. The interaction is a result of the sudden divergence between the occlusion and removal research scenarios estimates of T_c from the 6- to the 9-mph vehicle approach velocities and the relatively large decrease in bias for the occlusion research scenario from the 6- to the 9-mph vehicle approach velocity. The Research Scenario × Vehicle Approach Velocity interaction for the constant error analysis is displayed in Figure 12.

The main effect for age, $F(1, 18) = 6.48$, $p < .05$, indicated both younger and older participants underestimated T_c; however, the underestimation displayed by older participants was significantly greater than younger participants. The means for the younger and older participants were –.4 and –1.43 sec, respectively. The constant error main effect for age is illustrated in Figure 13 as a function of vehicle approach velocity. The Age × Vehicle Approach Velocity interaction, $F(3, 54) = 5.88$, $p < .01$, indicated that the bias in T_c estimates decreased for both younger and older participants with increases in the vehicle approach velocity. In general, younger participants exhibited less bias than older participants' and the disparity between younger and older participants bias in T_c estimates decreased with increases in the velocity of the approaching vehicle. This trend continued until the highest vehicle approach velocity tested, at which point the magnitude of bias of younger and older participants' estimates of T_c were nearly identical. The Age × Vehicle

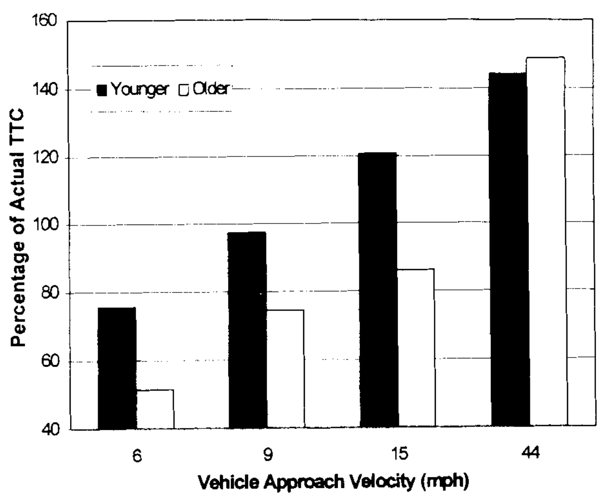

FIGURE 11 The Age × Vehicle Approach Velocity interaction for the actual time-to-contact (T_c) analysis. Note, the actual T_c means have been converted to a percentage of actual T_c for ease of comparison.

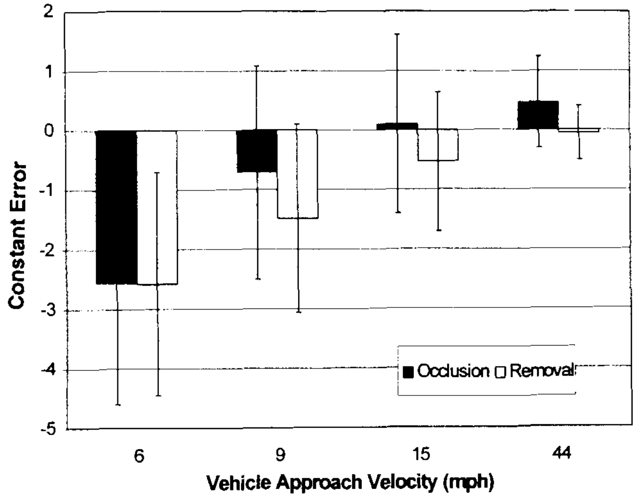

FIGURE 12 The Research Scenario × Vehicle Approach Velocity interaction for the constant error analysis. The interaction is due to the sudden divergence in constant error scores for both research scenarios from the 6- to the 9-mph vehicle-approach-velocity conditions.

Approach Velocity interaction is displayed in Figure 13. No other main effects or interactions in the constant error analysis were significant.

Absolute error analysis. The absolute error analysis indicated a main effect for vehicle approach velocity, a main effect for age, an Age × Vehicle Approach Velocity interaction, and an Age × Sex × Vehicle Approach Velocity interaction. The main effect for velocity, $F(3, 54) = 42.58$, $p < .01$, indicated that magnitude of absolute error in T_c estimates increased progressively as vehicle approach velocity increased. The means for the 6-, 9-, 15-, and 44-mph vehicle approach velocities were .57, 1.24, 1.86, and 2.86 sec, respectively. Post hoc analysis indicated that the 6- and 9-mph, 6-and 15-mph, 6- and 44-mph, and the 9- and 44-mph vehicle-approach-velocity means were significantly different from each other. The main effect for velocity is illustrated in Figure 14 as a function of participant age and participant sex. The main effect for age, $F(1, 18) = 5.46$, $p < .05$, indicated that the magnitude of absolute error for younger participants (1.42 sec) was significantly less than older participants (1.88 sec). The main effect for age is displayed in Figure 14 as a function of participant sex and vehicle approach velocity. The Age × Vehicle Approach Velocity interaction, $F(3, 54) = 4.38$, $p < .01$, indicated that older participants estimated T_c with greater absolute error for the 6-mph vehicle-approach-velocity condition as compared to the younger participants, that the differences between older and younger participants were nearly equal in the 9-, 15-, and 44-mph conditions.There was an Age × Sex × Vehicle Approach Velocity interaction, $F(3, 54) = 2.93, p < .05$, displayed in Figure 14. The interaction is due to the notably higher absolute error for older women at the lowest vehicle approach velocity as compared to younger women, older men, and younger men. It should be noted that the magnitude of absolute error for older women continued to be notably higher than all other groups at the two medium approach velocities, but was nearly identical to all other groups at the highest vehicle approach velocity tested. No other main effects or interactions were present in the absolute error analysis.

Variable error. The variable error analysis indicated a main effect for research scenario, a main effect for vehicle approach velocity, a Research Scenario × Vehicle Approach Velocity interaction, an Age × Sex interaction, a Sex × Research Scenario interaction, and a Research Scenario × Sex × Age interaction. The main effect for research scenario indicated that T_c estimates were more varied when participants viewed the occlusion research scenario (.93 sec) as compared to the removal research scenario (.55 sec), $F(1, 18) = 29.45, p < .01$. This main effect for research scenario is displayed in Figure 15 as a function of vehicle approach velocity. The main effect for vehicle approach velocity, $F(3, 54) = 42.45, p < .01$, indicated that participants' estimates of T_c become less varied as the velocity of the approaching vehicle increased. The means for the 6-, 9-, 15-, and 44-mph condi-

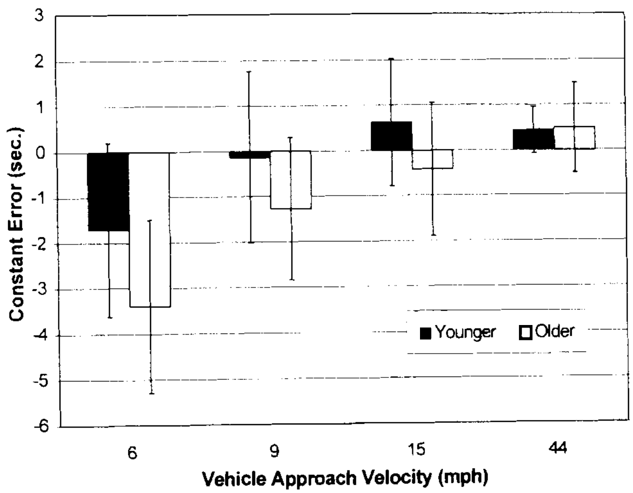

FIGURE 13 The Age × Vehicle Approach Velocity interaction for the constant error analysis. The interaction is a result of the convergence between younger and older participants's estimates of time-to-contact with progressive increases in vehicle approach velocity.

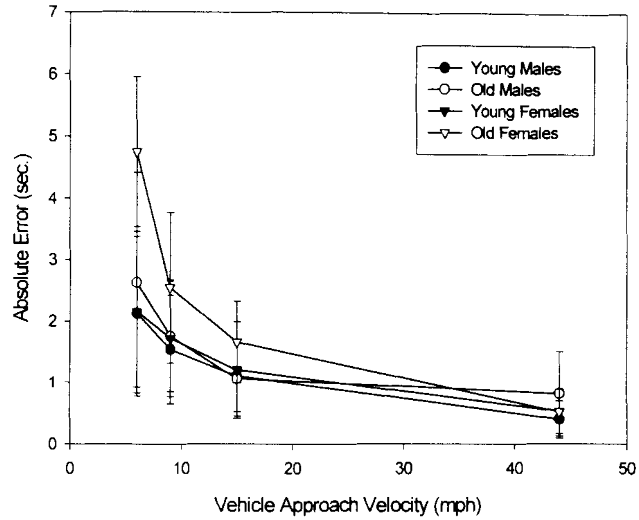

FIGURE 14 The Age × Sex × Vehicle Approach Velocity interaction for the absolute error analysis. The interaction is a result of the notable decrease in the magnitude of absolute error for older women with progressive increases in vehicle approach velocity.

tions were 1.25, .80, .59, and .32 sec, respectively. Post hoc analysis indicated all means were significantly different from each other except the 9-and 15-mph comparison. The main effect for vehicle approach velocity is displayed in Figure 15 as a function of research scenario. There was an interaction between research scenario and vehicle approach velocity $F(3, 54) = 8.91, p < .01$. The interaction is also illustrated in Figure 15. The interaction was a result of the dramatic decrease in variable error scores for the occlusion research scenario from the 6- to the 9-mph vehicle-approach-velocity condition as compared to the mild decrease in variable error scores for the removal research scenario condition for the same vehicle approach velocities.

There was an Age × Sex interaction, $F(1, 18) = 5.17, p < .05$, which indicated that younger men estimated T_c with less variability than younger women. However, this trend was reversed in older participants when the variability of T_c estimates for older female participants decreased sharply and the variability of T_c estimates for male participants increased slightly. This interaction is depicted in Figure 16 as a function of research scenario. There was an interaction between sex and research scenario, $F(1, 18) = 4.51, p < .05$. The interaction is depicted in Figure 16 as a function of participant age and is a result of men estimating T_c with more variability than women for the occlusion research scenario but estimating T_c with less variability than women for the removal research scenario. The Research Scenario × Sex × Age interaction, $F(1, 54) = 5.09, p < .05$, is also presented in Figure 16. Although three-way interactions are difficult to interpret, several interesting items emerge from the data. First, it is clear that for the occlusion research scenario mean variable error scores were greater for older men than for older women. Second, variable error scores of T_c for older men, younger men, older women, and younger women for the occlusion research scenario are nearly equidistant from each other. Third, there is a marked change in this patterning for the removal research scenario. Specifically, variable error scores for the removal research scenario became grouped according to participant sex, with men estimating T_c with less variability than women. Fourth, it is important to note that relative to older men, younger men, and younger women there is little difference between the mean variable error T_c scores for the occlusion and removal research scenarios for the older female participants. There were no other main effects or interactions in the variable error analysis.

Correlation Between T_c and Time-Production Estimates

Results of the Pearson product moment correlation between T_c and time-production estimates at each time interval resulted in an r of .35, .25, .35, and .44 for the 1-, 3-, 5-, and 7-sec time intervals, respectively (see Figure 17).

Summary of Results

In keeping with the results of the first experiment, this study indicated that participants estimated T_c with significantly greater accuracy and with significantly less bias when

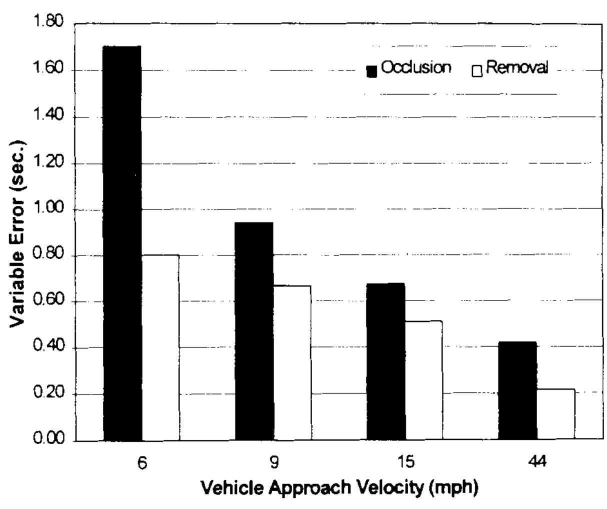

FIGURE 15 The interaction between vehicle approach velocity and research scenario for variable error. The interaction is a result of the dramatic decrease in variable error for the occlusion research scenario from the 6- to the 9-mph vehicle-approach-velocity condition as compared to the relatively mild decrease in variable error for the same vehicle approach velocities.

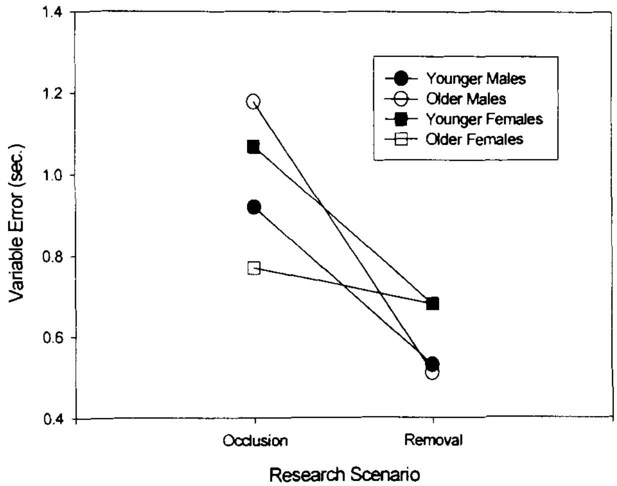

FIGURE 16 The Research Scenario × Sex × Age interaction for the variable error analysis. The interaction is a result of the relatively small change between variable error scores between the occlusion and removal research scenarios for the older female participants as compared to the other three groups.

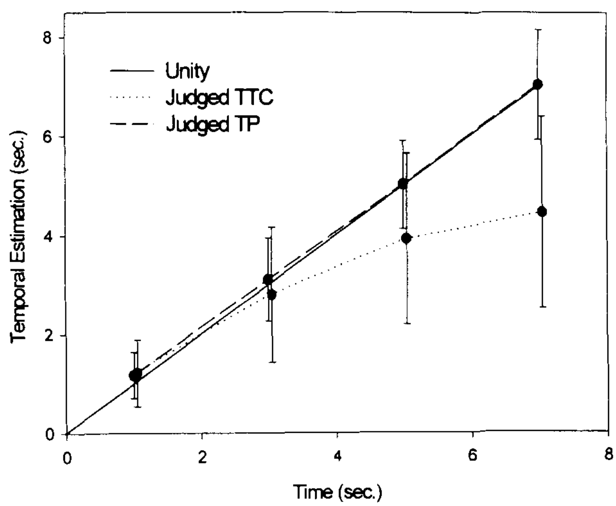

FIGURE 17 Mean and standard deviation for (T_c) and time-production estimates for each time interval. The Pearson product moment correlations between T_c and time-production estimates for the 1-, 3-, 5-, and 7-sec time intervals were .35, .25, .35, and .44, respectively.

the approaching vehicle was occluded by the naturally occurring object as opposed to disappearing instantaneously. Results also indicated that T_c estimates were more varied for the occlusion research scenario than for the removal research scenario.

However, research-scenario effects interacted with participant age and sex. Results confirmed sex differences and also supported those from Experiment 1 and previous research indicating that the accuracy of T_c estimates increases with progressive increases in the velocity of the approaching vehicle. It was found that older participants estimated T_c with greater bias than their younger counterparts. However, when the velocity of the approaching vehicle increased progressively, the levels of accuracy and the degree of bias between younger and older participants tended to converge. The time-production analysis confirmed that participants tended to overestimate time production, and the overestimations increased progressively with increasing time-production intervals. There was a relation between time production and T_c.

DISCUSSION

Research Scenario

The main effect for research scenario on T_c estimates (for Experiments 1 and 2), on absolute error (for Experiment 1), and on constant error of T_c (for Experiments 1 and 2) indicated that when an approaching vehicle was occluded by a naturally occurring object in the environment, T_c estimates were significantly more accurate and less biased than when an approaching vehicle spontaneously disappeared. When T_c responses were expressed as a percentage of actual T_c, the average level of accuracy for the removal research scenario for Experiments 1 and 2 were 76% and 71%, respectively, and were in line with the range of previous observations, indicating observers estimated T_c from approximately 55% to 75% (Caird & Hancock, 1994; Carel, 1961). However, participants viewing the occlusion research scenario in Experiments 1 and 2 estimated T_c significantly more accurately at 90% and 83%, respectively. The difference in mean accuracy between the removal and occlusion research scenarios for Experiments 1 and 2 were 14% and 12%, respectively. Consonant with the estimates of T_c, the constant error analysis indicated that the bias of T_c estimates for the occlusion research scenarios was significantly less than the removal research scenarios. Specifically, differences in the level of bias between the occlusion and removal research scenarios for Experiments 1 and 2 were .21 and .28 sec, respectively.

The absolute error analysis main effect for research scenario in Experiment 1 confirmed substantial differences between the occlusion and removal research scenarios. The means for the occlusion and removal research scenarios were .77 and .92 sec, respectively. These dramatic and consistently observed differences in accuracy and bias between the occlusion and removal research scenarios are crucial for research investigations of the tau theory.

The significant differences suggest that visual information in addition to affects the ability to determine T_c. According to a strict tau-based account of visual perception, the rate of image expansion of an approaching object on the retina is the only visual information needed to estimate T_c. Any additional visual information should not affect the accuracy of T_c estimates. In these experiments the rate of image expansion and the maximum visual angle subtended by the approaching vehicle were essentially identical in both the occlusion and removal research scenarios. The only difference between the two scenarios was in the method of removal of the approaching vehicle. In fact, because of limitations within the simulation itself, the approaching vehicle was present in the scene for a slightly longer time in the removal scenarios than for the occlusion scenarios. This kinematic situation resulted in a slight bias in favor of accuracy for the removal research scenario as participants were able to view the approaching vehicle for a fraction longer. The inference from these results is that knowledge of tau alone is not sufficient to predict how viewers estimate T_c (see also Heuer, 1993; Tresilian, 1994a; Wann, 1996). When the environmental context is elaborated from simple ball and grid patterns to more naturalistic situations, it is apparent that tau alone does not dictate an observer's response to objects on a collision course. Savelburg, Whiting, and Bootsma (1991) showed that tau plays a crucial role in a participants' ability to estimate accurately when to close their hand to successfully catch an approaching luminous ball in a darkened room. However, in this situation the only visual information available to the observer was that of the changing image size of the approaching ball. As a consequence, it is unsurprising that observers relied on tau solely in this situation. One of the implications of these findings is that in more naturalistic settings, such as occurs with the occlusion of the approaching vehicle in these experiments, there are other sources of visual information available that affect estimates of T_c (see also Wann, 1996).

Additional Sources of T_c Information

What are these other sources of T_c information, and why are observers more accurate estimating T_c when the approaching vehicle becomes occluded as opposed to disappearing? The answer to this question is tied to the implication of the results of these studies to the ecological approach to visual perception. The mode of disappearance of an approaching object evidently affects how T_c is judged. Researchers in allied fields indicated that participants can estimate time-to-coincidence when a moving stimulus is occluded by a stationary object (Reynolds, 1968; Yantis, 1995). Moreover, the occlusion of an object by a second object compared with the instantaneous object disappearance will elicit notably different responses in sucking responses in children (Bower, 1967). Recently, Li and Laurent (1995) compared rate of occlusion with tau information and demonstrated an effect for both on actions controlled by the information.

The findings that participants estimated T_c more accurately and with less bias when the approaching vehicle was occluded as compared to disappearing have direct implications for earlier proposals that have attempted to explain persistent T_c underestimations. Previous research indicated that there is a progressive underestimation of T_c as actual T_c increases (Caird & Hancock, 1994; Carel, 1961;

Knowles & Carel, 1958; Manser & Hancock, 1996; Schiff et al., 1992; Schiff & Oldak, 1990). Schiff and Oldak suggested that this progressive underestimation is a result of observers' attempts to obtain a greater *margin of safety* that would provide the observer with additional time to perform necessary actions to avoid unwanted contact. The implication of this underestimation is that inaccurate T_c estimates result in safer situations on roadways. This is one of the few occasions in experimental psychology in which the observer is applauded for being inaccurate. The margin of safety explanation is problematic because observers are notoriously inaccurate despite being told to respond when collision would have occurred. The results presented in this work indicate that observers reduced the so-called margin of safety significantly when the vehicle became invisible in a more realistic manner. This would indicate that a significant percentage of the underestimation is not founded on a strategy that leads an observer to err on the side of safety as proposed by Schiff and Oldak but, rather, is due to an ecologically less valid procedure for removing vehicles from the field of view. This observation challenges the conclusion that inaccuracy is necessarily good in these circumstances.

Results from Experiment 2 indicated significant differences in variable error between the two research scenarios and a variable error interaction between research scenario and vehicle approach velocity. In general, these results indicated that participants' T_c estimates were more varied for the occlusion research scenario than for the removal research scenario and that the variability of T_c estimates for both research scenarios decreased with progressive increases in vehicle approach velocity. The interaction was a result of the dramatic decrease in the variability of T_c estimates for the occlusion research scenario from low to medium vehicle approach velocities. There was also a Research Scenario × Sex × Age interaction for Experiment 2 that indicated that the variability of T_c estimates for older women remained stable between the occlusion and removal research scenarios relative to the notable decrease in variability for younger women, older men, and younger men. One possible cause for the increased variability of T_c estimates may be due to the process of object extrapolation performed by participants. It is possible that large variability in T_c estimates is inherent in normal driving situations as opposed to artificial acontextual laboratory settings. Another possibility derives again from the "snap" of disappearance providing a much more stable temporal cue to begin estimation as compared with the less precise occlusion event.

Factors Affecting T_c Estimates

Vehicle Approach Velocity

There are several established factors that appear to influence T_c estimates to a greater or lesser extent. The research presented here evaluated the influence of a limited number of these. The factors evaluated were the velocity of the approaching vehicle, the age of the participant, and the sex of the participant. The velocity of the approaching vehicle is one factor that appears to exert a strong and consistent influence on T_c estimates. For each experiment there were either main effects for vehicle approach velocity or interactions involving vehicle approach velocity. Regarding accuracy and bias, T_c estimates were influenced by vehicle approach velocity and age in Experiments 1 and 2. The findings indicated T_c estimates for older participants were less accurate and more biased than for the younger participants at low vehicle approach velocities, but the levels of accuracy and degrees of bias for both groups tended to become similar with progressive increases in vehicle approach velocity. Similarly, the variable error analysis indicated that the variability of T_c estimates for the occlusion research scenario was higher than the removal research scenario at low vehicle approach velocities, but the differences between the two research scenarios became suppressed with progressive increases in vehicle approach velocity. Collectively, these findings suggest increasing the velocity of the approaching vehicle acts to suppress differences between other factors that influence T_c estimates. Certainly, one reason why this suppression occurs is due the constraining of actions of the temporal and spatial requirements of the task (Hancock & Newell, 1985). The main effects and interactions between vehicle approach velocity and other factors influencing T_c estimates are discussed in the following.

Age Differences

The age of the participant is a factor that often affected T_c estimates. Several findings emerge from the age main effects for accuracy and bias, the Age × Vehicle Approach Velocity interactions for accuracy and bias, and the Age × Sex × Research Scenario interactions for variable error. First, findings from Experiments 1 and 2 indicated that T_c estimates for younger observers were more accurate than their older counterparts. Expressed as a percentage of actual T_c the levels of accuracy for younger and older participants for Experiment 1 were 87% and 77%, respectively, and for Experiment 2, 89% and 64%, respectively. Second, the findings from Experiments 1 and 2 indicated that T_c estimates for younger participants were less biased than their older counterparts. Specifically, constant error scores for younger and older participants in Experiment 1 were –.27 and –.49 sec, respectively, and for Experiments 1 and 2 were –.40 and –1.43 sec, respectively. Collectively, these findings confirm general differences between younger and older participants' ability to estimate T_c accurately and with little bias. Third, the findings from Experiments 1 and 2 indicated that the accuracy and bias of T_c estimates were influenced by both the age of the participant and the velocity of the approaching vehicle. The Age × Vehicle Approach Velocity interaction in Experiment 1 indicated that older observers became less accurate than their younger counterparts with increases in vehicle approach velocity. In this study, older participants were consistently less accurate than younger participants, and the net increase in percentage accuracy for older participants across the three approach velocities was only 5.5% whereas the net increase in accuracy for the younger participants was nearly twice that at 9%.

The Age × Vehicle Approach velocity interaction for the constant error analysis indicated that T_c estimates for both age groups became less biased with increases in vehicle approach velocity and that the disparity in the bias of T_c estimates between the two age groups became greater at higher vehicle approach velocities. Contrary to Experiment 1, Experiment 2 indicated that the bias of T_c estimates for younger and older participants converged with increases in vehicle approach velocity but over a larger range of kinematic conditions. T_c estimates for both age groups became less biased with increases in vehicle approach velocity. Differences in the bias between younger and older participants decreased with increasing vehicle approach velocities. These findings are in contrast with those of Experiment 1. The inconsistent Age × Vehicle Approach Velocity interactions for accuracy and bias of T_c estimates in Experiments 1 and 2 suggests that only general trends regarding accuracy and bias between younger and older participants can be confirmed. The first trend is that estimates of T_c for younger participants are more accurate and less biased than older participants, and the second trend is that estimates of T_c become more accurate and less biased for both younger and older participants with progressive increases in vehicle approach velocity. Clearly these trends are, in part, contingent on the specific kinematic conditions investigated.

Two additional age findings emerged from Experiment 2. First, there was an Age × Sex × Vehicle Approach Velocity interaction for absolute error that indicated that in general the magnitude of absolute error of T_c estimates for all Age × Sex groups progressively decreased with increased vehicle approach velocities. What cannot be ignored is the notably larger magnitude of absolute error displayed by older women as compared to younger women, older men, and younger men at the lowest vehicle approach velocity tested. Although not as great, the magnitude of absolute error for older female participants is notably higher than all other groups for the two middle vehicle approach velocities tested. Only at the highest vehicle approach velocity tested does the magnitude of absolute error for older women became aligned with the magnitude of absolute error for the other three groups. Due to the lack of other research examining the influence of age, sex, and vehicle approach velocity on T_c estimates this finding is, as yet, unconfirmed. However, support for the effects of age and sex factors is provided by similar interactions reported by Schiff et al. (1992). Results of their study indicated that older women estimated T_c significantly less accurately than younger women, older men, and younger men. A second finding from Experiment 2 was the Research Scenario × Age × Sex interaction for variable error. The interaction indicated that the amount of variability in T_c estimates for older women was relatively stable between the occlusion and removal research scenarios, but the amount of variability for younger women, older men, and younger men decreased markedly from the occlusion research scenario to the removal research scenario. It should be noted that the variability of T_c estimates for older women for the occlusion research scenario was equal to younger women and lower than younger and older men for the removal research scenario. Collectively, the findings from Experiments 1 and 2 indicate substantial differences between younger and older participants' ability to estimate T_c and that these differences interact with the sex of the participant. In particular, older female participants displayed a greater magnitude of absolute error at low vehicle approach velocities as compared to younger women, older men, and younger men. However, these differences diminished at higher vehicle approach velocities.

Sex Differences

Previous work has indicated that men and women differ in their ability to estimate T_c (Caird & Hancock, 1994; Manser & Hancock, 1996; McLeod & Ross, 1983; Schiff & Oldak, 1990). However, there were no significant differences between men's and women's estimates of T_c in Experiment 1. One potential reason for this lack of sex differences may have been the relatively small range of T_c investigated (1.95, 2.19, and 2.49 sec) as compared to the range of T_c for studies that have found differences. For example, T_cs have ranged from 1 to 7 sec (Caird & Hancock), 3 to 6 sec (Manser & Hancock), and 1.5 to 6 sec (Schiff & Oldak, 1990). A second reason for the lack of sex differences may have been due not solely to the relative range of times chosen, but their low absolute values as well. Consequently, windowing the lower end of the T_c range may have masked sex differences. Experiment 2 used a range of T_cs from 1 to 7 sec and indicated significant differences between men and women in the magnitude and variability of T_c estimates. Specifically, the findings of Experiment 2 indicated that women estimated T_c with greater absolute error but less variability than men. These differences were a direct result of the interactive effects with participant age, research scenario, and vehicle approach velocity. The Age × Sex × Vehicle Approach Velocity interaction for absolute error indicated that at the lowest vehicle approach velocity the magnitude of absolute error for older female participants was notably higher than for younger women, younger men, and older men. Although not as pronounced, a similar pattern existed for the two medium approach velocities tested. It was only at the highest vehicle approach velocity tested that the magnitude of absolute error for older women was similar to younger women, older men, and younger men. Nearly identical trends for sex and vehicle approach velocity for accuracy of T_c estimates were observed by Caird and Hancock and Manser and Hancock. In particular, both of the former studies showed that women underestimate T_c considerably more than men when the vehicle approached at the low to medium velocities tested and that at the highest vehicle approach velocity tested, women were slightly more accurate than men. Additional support confirming differences between men and women comes from the Age × Sex × Research Scenario interaction for variable error. The interaction indicated that the amount of variation in estimates of T_c for younger women, older men, and younger women was less for the removal research scenario than for the occlusion research scenario, perhaps indicating that, as noted earlier, the disappearance event itself provided a better temporal marker than the more gradual occlusion event. However, the variability in estimates of T_c for older women was similar for the two research scenarios. These results of Experiment 2 confirmed the propositions that differences between men and women depend, in part, on the range and absolute values of T_c.

Similar trends supporting the age and sex interactions for overall accuracy have emerged from research performed by Schiff et al. (1992). Their work indicated that the accuracy of T_c estimates for older female participants was considerably less than younger female, older male, and younger male participants. In addition, Schiff and Oldak (1990) found that women estimated T_c significantly less accurately than men. As a result of these findings, and the converging evidence of others (Caird & Hancock, 1994; Manser & Hancock, 1996; McLeod & Ross, 1983; Schiff et al., 1992; Schiff & Oldak, 1990), differences in the accuracy and the variability of estimates of T_c for male and female participants are confirmed.

The results of Experiment 2 indicated that differences between men's and women's ability to estimate T_c depends on the range of T_c used. The primary question now becomes "How large of range of T_c is necessary to exhibit statistically reliable differences between men and women?" Previous experiments that have found differences between men and women (Caird & Hancock, 1994; Manser & Hancock, 1996; McLeod & Ross, 1983; Schiff et al. 1992; Schiff & Oldak, 1990) used ranges of T_c greater than 3 sec. It would appear that at least this duration is required for the accumulation of a difference to reach traditional significance values.

Relation Between Time Estimation and T_c

In earlier work, Schiff and his colleagues attempted to test whether estimates of T_c were related to the ability to estimate duration when no stimulation was presented (Schiff & Oldak, 1990). They found no such linkage. Hancock (1998b) criticized this finding because Schiff and his colleagues used a time-reproduction procedure that is inappropriately matched to the time-production procedure required in estimates of T_c (see also Black, 1990). In research on temporal faculties, the methodology exerts a crucial influence on the outcome observed. Here, we have tried to rectify this methodological mismatch by using a time-production procedure with the same temporal structures as the T_c task. As can be seen from the results, there is some relation between the two capabilities. However, exactly how these two temporal faculties are linked awaits further critical elucidation.

Recommendations

In the field of applications of psychological research, it is critical to evaluate how experimental results affect performance in real-world settings. The primary outcome of this research is that investigations directed toward T_c issues require as veridical a test situation as possible because environmental context clearly influences outcome. These results imply that previous speculation about safety margins, adopted as purposive strategies by drivers, in T_c are much less liable to account for the underestimation than artificialities introduced into the assessment method, in this case, spontaneous disappearance. The work further emphasizes the remarkable, adaptive capabilities of the visual perceptual system and consequently casts doubt on the feasibility of totally automated collision detection and avoidance systems, as presently envisioned in Intelligent Transportation Systems (ITS) implementations (for critiques, see Hancock et al., 1991; Hancock, Parasuraman, & Byrne, 1996; Parasuraman, Hancock, & Olofinboba, 1997). Failure to recognize the remarkably efficient nature of intrinsic human collision-avoidance abilities may therefore fracture a tenet of safety, *primum non nocere* (first, do no harm).

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