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DRIVER WORKLOAD DURING DIFFERING DRIVING MANEUVERS

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Abstract—Motorcycle-automobile accidents occur predominantly when the car driver turns left across the motorcyclist's right-of-way. Efforts to decrease this specific collision configuration, through an increase in motorcycle conspicuity, have concentrated on the physical characteristics of the motorcycle and its rider. The work reported here examines the behavior of car drivers during different driving sequences, in particular during left-turn maneuvers. An experiment is reported that used simultaneous video-taping of the driver and the forward-looking scene. Subjects followed a preset on-road course and were observed for head movements to determine the possibility of structural interference eye-blink frequency, probe-response time, and probe response error, as measures of cognitive or mental workload. In addition, the subjects completed two major subjective workload evaluations as reflections of effort directed to different components of the driving task. Results indicated that there were significant increases in head movements and mental workload during turn sequences compared to straight driving. This result of higher driver workload may be responsible for increasing the potential for detection failure. Such a propensity is also fostered by the higher structural interference that may be expected during turns. Failures to observe during turning sequences have differing outcomes depending on the presence of opposing traffic, as during the left turn, compared with the absence of such opposition, as occurs in the right turn. Also, the less conspicuous the oncoming vehicle in the left turn scenario, the higher the probability of detection failure. At the present time the least conspicuous powered vehicle is the motorcycle.

INTRODUCTION

The leading cause of death among young people in urbanized societies is road traffic accidents. Such fatalities are not evenly distributed across different types of vehicles. Comparative data from a number of sources indicate the significantly higher propensity for fatality for drivers using a motorcycle compared to other vehicles. In the United States in 1986, for example, motorcycles comprised 2.9% of the total vehicle registrations but were involved in 7.9% of the fatal accidents (National Safety Council 1987). This problem is not confined to the United States. Comparable accident data are even less favorable for motorcyclists in other countries. In West Germany in the same year, 4.4% of all registered vehicles were motorcycles; however, their involvement in fatal accidents was 15.6% (Allgemeiner Deutscher Automobil-Club 1987). Using miles traveled as a baseline, the death rate in the United States for motorcycle riders is approximately 35 per 100,000,000 miles. This is about 13.6 times higher than the overall death rate of 2.57 per 100,000,000 miles (National Safety Council 1987). In West Germany, the kilometer death rate is 44 times higher for motorcyclists than for automobile drivers (Appel et al. 1986).

The high fatality rate of motorcyclists leads to a dominant and prevailing misconception that it is the motorcycle itself, or its control characteristics in conjunction with its driver, that are the source of the problem. Analysis of actual accidents indicates otherwise. In nine of the leading ten accident configurations involving a motorcycle and an automobile, it is the automobile driver's violation of the motorcyclist's right-of-way that leads to the critical incident (Hancock et al. 1986; Hurt et al. 1981). Subsequent analyses of automobile-motorcycle collisions show the dominance of a single accident configuration (e.g. Waller 1972; Olson et al. 1979a, 1979b; Weber and Otte 1980; Hurt et al. 1981). This type of accident is portrayed on those occasions when the automobile driver violates the motorcyclist's right-of-way by making a left turn into the path of the oncoming motorcycle. This situation is presented schematically in Figure 1. In postaccident interviews, the driver frequently claims not to have seen the motorcycle.

In attempts to reduce the frequency of motorcycle-automobile collisions considerable effort has been directed to the question of the physical characteristics of the motorcycle and its rider. These manipulations have tried to improve the probability of detecting the motorcycle through changes in *conspicuity*. Conspicuity can be defined as the degree to which an object can be distinguished from an environmental display; that is, its visual prominence based on its physical characteristics with respect to the background against which it is set. Clearly, this distinction has to be specified upon a number of axes, which are typically those which connote the dynamic visual environment, e.g. object size and constancy, reflected wavelength. These factors, which represent the physical qualities of an object that can be compared using external reference measures, should be referred to, more appropriately, as *sensory conspicuity* (Engel 1976). Numerous studies have focused on the characteristics of the motorcycle that affect conspicuity, such as running the headlight during the daytime (e.g. Janoff and Cassel 1971; Janoff 1973; Fulton et al. 1980; Dahlstedt 1986) or fairings that increase the frontal surface area (Williams and Hoffmann 1977, 1979). These studies have been complemented by examinations of conspicuity manipulations to the rider, such as the wearing of fluorescent garments (e.g. Stroud and Kirkby 1976; Stroud, 1980; Donne and Fulton 1985; Olson et al. 1979a, 1979b, 1981) to enhance the potential for detection by other drivers. These studies have been reviewed by Wulf (1989).

A second form of conspicuity is *cognitive conspicuity*. This form of conspicuity is specifically contingent upon the characteristics of the observer and relies critically on

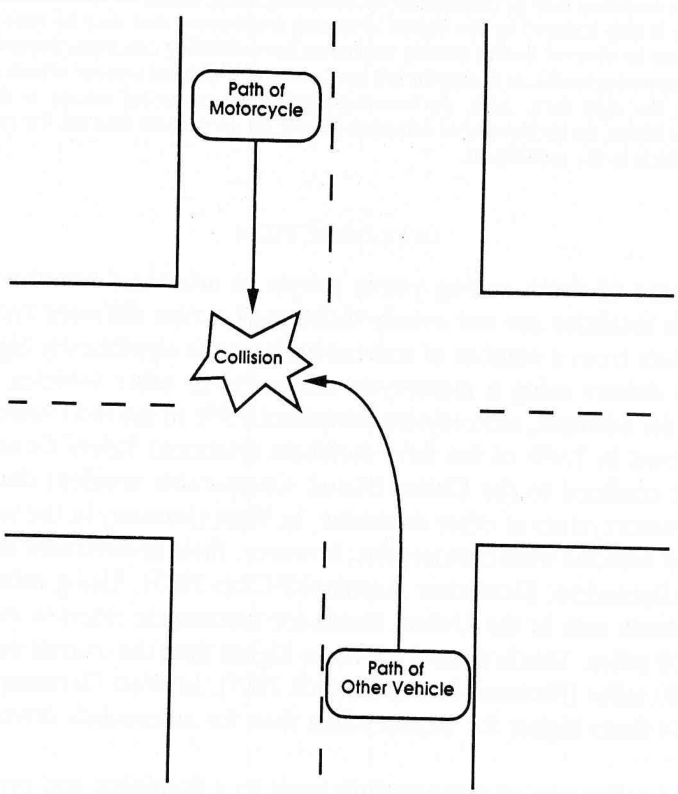

Fig. 1. Predominant automobile-motorcycle accident configuration sees an automobile driver turning left across and violating the right-of-way of the motorcycle rider. Reasons for the detection failures that lead to this particular configuration are examined in the text.

the salience of the target, or its meaning with respect to the observer's existing goals. Cognitive conspicuity depends on the previous experience and momentary intentions of the observer. There are indications that this aspect of conspicuity plays a role in failure to detect motorcycles. Postaccident interviews by Hurt et al. (1981) recorded that automobile drivers involved in collisions with motorcycles were usually "unfamiliar" with motorcycles. Also, Weber and Otte (1980) working in West Germany reported that among automobile drivers involved in a collision with a motorcycle, those without a driver's license for a motorcycle were overrepresented. It is the contention of the present work that the failure of detection is the result of a complex interplay between the observer and the object being observed. While many studies have manipulated elements of the object, few have examined the characteristics of the observer while involved in the task of on-road control.

Therefore, the present experiment examined limitations in automobile drivers' information processing and the competition for limited processing resources which affect the driver efficiency in detecting oncoming motorcycles during left-turn sequences. These capabilities were assessed by means of measures such as probe-response time and associated error, as well as eye-blink frequency, which have been found useful in measuring mental workload (Hancock and Meshkati 1988). Also, driver subjective load was evaluated before, during, and after the test drive. Finally, head-reversal frequency was measured to determine possible limitations to visual information processing.

METHOD

Subjects

Eighteen subjects (10 females and 8 males) were recruited from the staff and faculty of the Institute of Safety and Systems Management at the University of Southern California. Their ages ranged between 21 and 50 with a mean age of 30 years. Subjects were not paid for their participation, and all were naive as to the purpose of the experiment. Each subject possessed a current California State driver's license and the visual capabilities that the license requires.

Task and procedure

The driver's task was to negotiate a preset course of nonfreeway urban streets in Los Angeles. The course consisted of 10 left turns and 10 right turns interspersed with straight sections. The time required to complete the route varied with the individual driver and traffic, but was always between 12 and 18 minutes long. Each subject was guided through the course by an experimenter sitting in the passenger seat of the car. The experimenter also activated a switch to turn on a probe light at random intervals during various turn and straight sequences. The probe light was mounted on the dashboard directly in front of the driver. The subject was required to turn off the light as rapidly as possible after detection by pressing a button that was attached to the dashboard to the left of the steering wheel. In addition to these measures, the subject was asked to complete two subjective mental workload procedures, which are described below. The subject was required to complete portions of each procedure before and following the driving sequence. One of the procedures also required response during driving.

Workload assessment techniques

The two procedures chosen to assess subjective workload response were the NASA *Task Load Index* (TLX) procedure and the USAF *Subjective Workload Assessment Technique* (SWAT) (see Hart and Staveland 1988; Reid and Nygren 1988). Their administration is described below. The TLX consists of a two-step sequence, one step of which is completed prior to the experimental procedure, and one which follows performance termination. In the first step, the participant compares the six dimensions of workload against each other in a pairwise fashion to establish which of each pair is perceived to contribute the greater source of load. The dimensions are: mental demand (md), physical demand (pd), temporal demand (td), effort (ef), performance (op), and frustration (fr).

The weighting of each scale depends upon the number of times that scale is selected in the fifteen total comparisons. The weights, therefore, can vary between 0 and 5. The second step of the TLX process requires the subject to rate the load of the drive on a 0–100 scale for each of the six dimensions. These are the raw scores for each scale. The raw scores are multiplied by their respective weights to derive weighted scores, and the overall workload value is the sum of all weighted scores divided by fifteen, the original number of pairwise comparisons. In the present experiment, the subjects rated the driving sequence they had just performed against a nominal drive of equivalent duration that they experience in their normal commute to work. It was these data that were subject to analysis.

The SWAT technique also consists of two stages. The first stage is a card-sort procedure in which the participant sorts 27 cards that contain statements about the time, effort, and stress load of performance. Each card consists of three statements that describe three ascending load conditions on each scale. It is the matrix of three scales by three loads in combination that give the 27 possible combinations. The subject sorts these combinations in the order of perceived ascending load, and a workload scale is derived from the individual's responses. The second phase is the event-scoring phase in which subjects rate the event that has just occurred on one of three levels for each of the time, effort, and stress scales. In the present experiment, subjects rated performance following the driving sequence and, as with the TLX, compared this with a nominal commute to work. In addition, some subjects were asked to give several three-number SWAT ratings during the driving sequences. These overall data were subjected to analysis as reported below.

Apparatus

Driver behavior was recorded through the use of two simultaneous, linked video cameras and recorders. All experimental trials were conducted in a 1988 Ford Ltd. Crown Victoria. In order to analyze drivers' head and eye movements, split-screen video recording was used. This technique time-locked the two video cameras. One camera was mounted on the windshield in front of the driver, but above the driver's line of forward sight. This camera was trained on the driver's face. The other camera was mounted on the roof of the car, directly above the driver's head, and recorded the visual field available to the driver in front of the car. A light connected in series with the probe light on the dashboard was attached to the headrest of the driver's seat and recorded by the first camera. The subject's activations of the throttle and brake lights were monitored as well, using lights located in the same area. This was achieved by using microswitch-activated light-emitting diodes (LEDs). Microswitches mounted on the floor of the car were activated by slight pressure on the throttle or brake pedal, and lit the respective LED. The LEDs were attached to the headrest of the driver's seat, along with the probe light. The output was such that approximately half of the image of the external camera occupied the lower portion of the video screen, and half of the image of the internal camera occupied the upper portion of the screen. This split-screen tape was postprocessed to add a timer from which subsequent measures were taken.

RESULTS

A digital time display was added to the split-screen tape. The clock gave time in terms of hours, minutes, seconds, and frames (30 per second). The time required to respond to the probe light, together with the associated error rate, as well as the overall time for each turn and straight-lane sequence was recorded from this screen timer. The start and end of each turn sequence was defined by the deactivation of the throttle LED, and the achievement of a car position parallel to the street, respectively. For each turn sequence the number of eye blinks and head reversals were recorded and their rate per second was derived for analysis. The dependent variables were then analyzed against the driving sequence in which they occurred. Analyses of variance were performed for each dependent variable. For probe-response time and probe-response error, one-way

ANOVAs were performed on the three driving maneuvers, i.e. left turns, right turns, and straight sequences. The analyses for eye-blink frequency and head reversal frequency involved a two (probe condition, present or absent) by three (maneuver, left turn vs. right turn vs. straight driving) model. Fisher's test was used for the post hoc comparison of means.

Head-reversal frequency

Head reversals were defined as an observed change in the direction of head movement. Simply continuing or accelerating an ongoing movement was not recorded as a reversal. Such measures were taken from the postprocessed video tape of the driver's performance. The significance of this measure is related to the question of simple structural interference. It is probable that ascending head-reversal frequency increases the possibility that a target may be missed simply because the observer is looking in another direction. So, this measure of structural interference augments the assessments of more central limitations resulting from cognitive load. With regard to the head-reversals frequency, there was a significant effect of probe condition, $F\,(1{,}625) = 7.33$, $p < .01$. The number of head reversals per second was generally higher for the sequences that included a probe (.209) than for maneuvers without a probe (.169). No significant interaction between probe condition and driving maneuver was found. The main effect of maneuver was statistically significant, $F\,(2{,}625) = 24.37$, $p < .001$. The head-reversal frequency per second was higher during left turns (.255) and right turns (.253) than during straight-lane driving (.127). These data are illustrated in Figure 2. Post hoc tests indicated that both the differences between left turns and straight-lane driving, and between right turns and straight-lane driving were significant ($ps < .05$). Also, the intra-individual variances were significantly ($ps < .001$) higher for both left turns (.055) and right turns (.055) than for straight-lane driving (.021).

Eye-blink frequency

For eye-blink frequency, there was no significant effect of probe condition, or interaction of probe condition and driving maneuver. The main effect of maneuver, however, was significant, $F\,(2{,}610) = 5.68$, $p < .01$. Overall, the number of eye blinks per second was lower for left turns (.310) and right turns (.290) than for straight sequences (.376). These data are presented in Fig. 3. Post hoc comparisons indicated that the

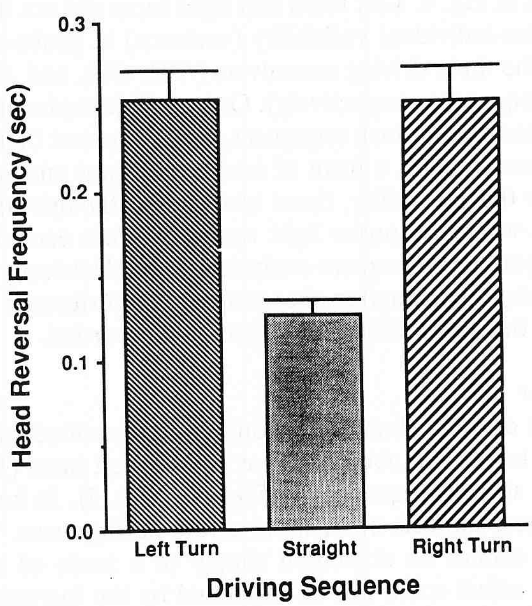

Fig. 2. Head-reversal frequency, number per second, during differing driving sequences. The large difference between straight driving and turning maneuvers is apparent. The height of each column represents the mean response, with the vertical T bar indicating the standard error.

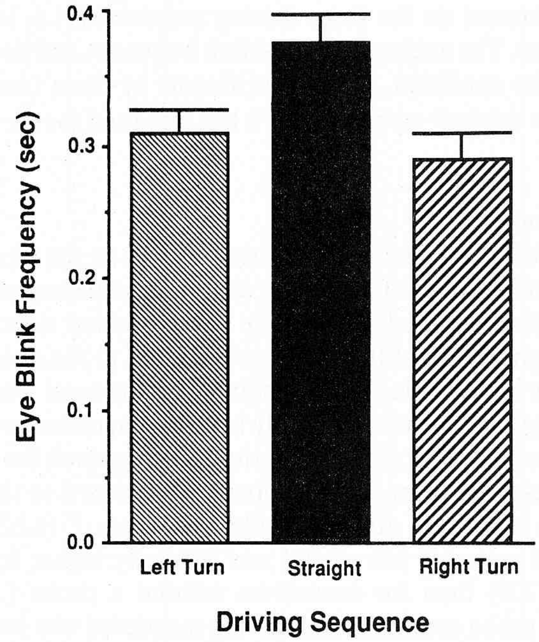

Fig. 3. Eye-blink frequency, number per second, during different driving sequences. The suppression of eye blinks during turn sequences is evident, and is further supported by significant depression in blink rate variability during turns. The height of each column represents the mean response with the vertical T bar indicating the standard error.

differences between turn conditions and the straight-driving condition were significant ($ps < .05$), while there was no significant difference between left and right turns. The intra-individual variance in eye-blink frequency was about 2.5 times higher during straight driving sequences (.100) than during left (.037) and right turns (.039), respectively.

Probe-response time

For probe-response time, the ANOVA revealed a significant effect of maneuver, F (2,235) = 9.43, $p < .001$. Post hoc analysis indicated that the time needed to respond to the stimulus light was significantly ($ps < .05$) longer for left-turn (2.01 sec) and right-turn sequences (1.84 sec), as compared to straight-lane driving (1.48 sec). These differences are illustrated in Fig. 4. Left turns and right turns did not differ significantly from each other. The intra-individual variability (variance) in probe-response time differed only minimally for the three driving maneuvers (.702, .501, and .592, for left turns, right turns, and straight sequences, respectively). One possible explanation for the first finding is that during the execution of turn sequences, drivers turned their heads away from the centrally placed stimulus light, a form of interference not encountered during straight driving. To examine this possibility, those turns where the drivers turned their heads in a different position when the probe light came on, were excluded from the analysis. However, results from this subsequent analysis remained basically unchanged. This finding contradicts a simple explanation that structural interference due to head position was responsible for the probe differences that were recorded.

Probe-response error

Response times of more than five seconds were classified as response errors. The number of response errors was about twice as high for left turns (13.8%) and right turns (12.0%), relative to straight sequences (5.5%) (see Fig. 5). In keeping with the results for the response times, subjects made more errors during turns. Thus results observed in the latency data cannot be attributed simply to a trade of speed for accuracy in response. Also, this effect could not be explained by the increase in head movements during maneuvers. Without those cases, in which the driver looked in a different direction when the probe light came on, response errors amounted to 13.2%. This finding contradicts a simple speed-accuracy trade-off in response to the probe light in this task. So,

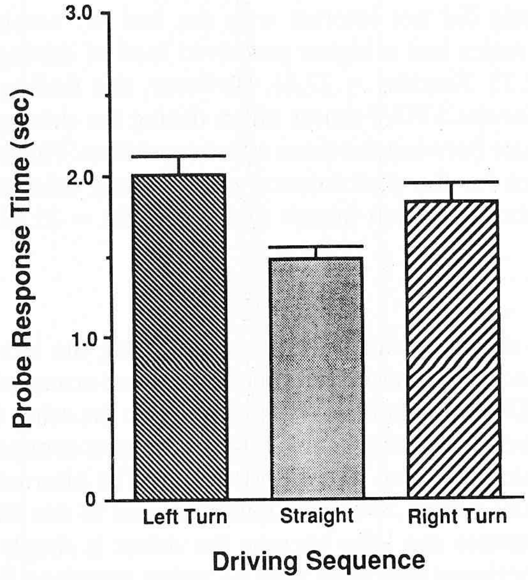

Fig. 4. Probe-response time during different driving sequences. Elevation in response time is not due to simple structural effects such as looking in another direction. Also data are not the subject of a speed-accuracy trade-off as illustrated also in Figure 6. The height of each column represents the mean response with the vertical T bar indicating the standard error.

failure to notice the stimulus light during turns cannot also be attributed simply to an interference effect. Both latency and accuracy of probe responses point to the increase in central processing time during the more difficult turn sequences.

Subjective workload responses

The first analysis of workload concerned the comparison of the present drive vs. a nominal drive to work. If the analysis had found any differences, it would suggest that the present driving sequence was different from a normal commute. However, analysis indicated no significant differences in perceived workload of the present test sequence in comparison to a normal drive to work. This finding was consistent for both the TLX and SWAT procedures. Interestingly, there was a significant difference for the TLX score

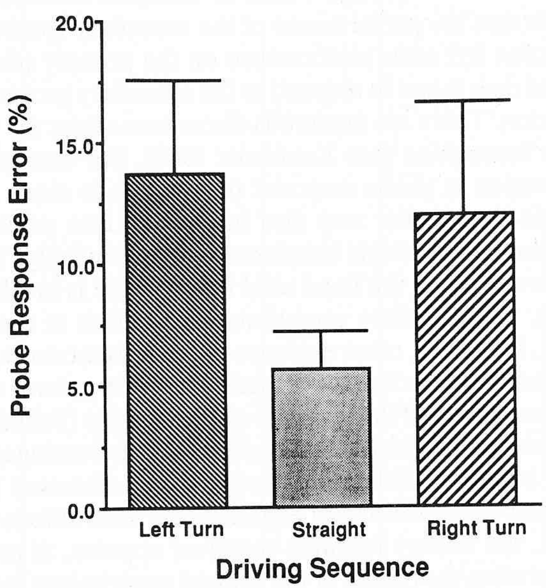

Fig. 5. Percentage probe errors during differing driving sequences confirm that more errors are made during turns in comparison to straight driving. The height of each column represents the mean response with the vertical T bar indicating the standard error.

for gender. While this did not interact with the test vs. nominal driving sequence, responses indicated males had a higher perceived load of driving compared to female drivers (Males = 42.33, Females = 27.6). However, this finding was not replicated in the SWAT scores. For the SWAT scores taken during the driving sequence, there was no significant difference between the three noted conditions. However, there was a trend in the direction noted for the performance variables and other measures of workload given in the results above (i.e. left turn = 27.58, straight = 25.42, right turn = 34.29).

DISCUSSION

With respect to detection failures that occur during the left-turn sequence, there are two lines of evidence to be considered. The first centers around the significant increase in head movements. Detection failures due to looking in the other direction are regarded as *structural interference*. This can take two forms. The most common form is the masking of the oncoming vehicle by some visual obstruction. The alternate form relates to the restriction of the visual system. We have limited access to the 360 degree visual field, and structural interference can arise because the driver is simply looking in the other direction. To the experimentalist these may be rather mundane findings, however, our evidence from the drivers' increasing propensity to head movement during turns warns that such behavior can be an important source of detection failure. Data indicate that there was no significant difference between head movements for the left- and right-turn sequences. However, the result of a detection failure when turning across traffic is clearly different than the result of such a failure when turning with no opposing oncoming vehicles. It is also reasonable to suggest that structural interference due to head movement is more likely to result in missed targets with smaller frontal surface area rather than larger frontal surface area simply from the absolute area that such a target occupies on the retina.

The second line of evidence addressed by the present data is *resource competition*. It is postulated that there are some limits to the central processing capability. Differing performance demands tax the central processing capability to differing degrees. One theory that uses the concept of a limited central capability is the unitary attentional resource model of human information processing. Despite extensions into multiple resource constructs (Wickens 1987), which provide explanatory power at the expense of additional degrees of freedom, the unitary resource model (Kahneman 1973) is usually taken as the modal construct through which to interpret secondary task information. The basic rationale is that the performance of the secondary (probe) task is a reflection of the residual attention left after performance on the primary (driving) task is accomplished. The length of time taken to respond to the secondary probe is taken as a measure of the residual attention. There are numerous discussions about the validity of this model and particularly this assumption (see Kantowitz 1987). For example, it may be argued that the present elevation in probe response time is due to more motoric components of task demand. This explanation may also be divided into potential competition for central processing resources or simple interference to limb activity. The latter case argues that responses are slowed when the hand used for response is involved in turning rather than straight driving, and therefore represents competition at the response execution stage (Schmidt 1982). However, other evidence in the present study, e.g. eye-blink data, support the contention that interference is more central in nature, and, in motor terms, this would suggest competition at the response selection stage (Schmidt 1982). Identifying the locus of interference at this response selection stage is contingent upon assumptions about the model of attention underlying processing as discussed above. In light of a number of contemporary theoretical and experimental reservations concerning the multiple resource model, the unitary resource construct appears, at present, to be a more useful basis for interpreting the results of the present experiments (see Kantowitz, 1987).

In the present findings, it is clear that processing time to the secondary task is increased with the difficulty of the driving maneuver between turning and straight driving. These findings are in line with those of Miura (1986, 1987). He examined driver response to stimulus lights on the windshield that were illuminated at differing spatial locations and at random intervals. Miura found that as the situational demands increased (driving in highly-crowded downtown traffic compared to a much less crowded one-way route), the associated reaction time also increased. Also, higher demands resulted in a narrower functional visual field. It should be noted that during turning maneuvers it is oftentimes necessary to suppress vestibular nystagmus, and such suppression may also be implicated in the ascending attentional demands of such maneuvers as the present data show.

In a number of experimental procedures (see Hancock and Meshkati 1988), processing time to the secondary task is taken as a direct reflection of the mental workload demanded by the task. In our experiments, this assertion was supported by the findings for the physiological reflection of workload as reflected in eye blinks per second (Hancock, Meshkati, and Robertson 1985). It has been observed that as subjects increase mental effort, particularly with respect to a visual task, the eye-blink response is suppressed. In our experiment, we found a significant depression, depending upon driving sequence, that followed the probe response time. The findings for subjective workload response presented a somewhat supportive pattern of data. First, it was established that there was no significant difference between the test drive and a nominal commute with similar road conditions. Although a number of cautions have been raised concerning the influence of memory on subjective ratings (Eggemeier, Melville, and Crabtree 1984), the present data indicate that subjects found driving the test car to be a load similar to that of this usual commute. The data concerning subjective workload probes taken during the driving sequence indicated no significant effects for driving maneuver on perceived workload. However, examination of the actual response indicates a propensity toward higher workload during turn sequences in accord with the other workload measures. As with all recorded responses, however, there were dominating effects for individual differences. Indeed, one of the major findings of our experiment was the range of responses recorded across differing individuals each faced with the same common performance task.

In summary, the results point to the conclusion that the responses involved in turning sequences are liable to increase detection failures through increasing structural interference and through the reduced processing capability that remains when a more difficult performance response is demanded. In the latter condition, less residual attention is available to monitor the surrounding environment for potential sources of threat, particularly those which present the observer with sources of relatively low cognitive conspicuity. This finding dovetails nicely with the observations of performance under stress, where a functional attentional "narrowing" occurs as greater stress is imposed (Easterbrook 1959). In the present case, the stress is the increased demand of driving difficulty. Also, the present findings are allied to previous use of mental workload techniques to evaluate driving performance (for a critique see Noy 1987). Understanding intention driven perception-action systems in a complex visual world is a difficult challenge. Understanding the etiology of rare collision events where actual information about precollision behavior is inaccessible is even more so. The price of ignorance with respect to such understanding is the continuation of serious and often fatal injury to motorcycle riders and other road users.

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