DRIVER COMPREHENSION OF INTEGRATED COLLISION AVOIDANCE SYSTEM ALERTS PRESENTED THROUGH A HAPTIC DRIVER SEAT

Gregory M. Fitch[1], Jonathan M. Hankey[1], Brian M. Kleiner[2]
[1]Virginia Tech Transportation Institute
[2]Virginia Tech
Blacksburg, Virginia, USA
Email: gfitch@vtti.vt.edu

Summary: The purpose of this study was to quantify the effects of increasing the number of collision avoidance system alerts presented through a haptic driver seat on drivers' response performance. Twenty-four participants performed specific driving maneuvers in response to one, three, or seven haptic seat alerts while they drove an instrumented vehicle. Participants verbally identified the alerts after executing a maneuver. Results show that drivers made the correct driving maneuver in response to the alerts. This was likely because of the strong stimulus-response compatibility designed into the haptic seat. As predicted by Information Theory, drivers' mean manual response time to the alerts significantly increased, and their verbal response accuracy significantly degraded, as the number of alerts increased. A three-alert haptic seat approach is recommended providing specific design requirements are met.

INTRODUCTION

Active safety systems that warn drivers of impending collisions have been developed. How these systems alert drivers when amalgamated, however, is a crucial component to their effectiveness that hinges on the consideration of human factors. Drivers must be able to quickly perceive, process, and execute the correct maneuver in response to the alerts in order to avoid a collision. Active safety system designers should question whether drivers can efficiently process various alerts. Information Theory (Shannon & Weaver, 1949) states that the amount of information conveyed by an event is a function of: 1) the number of differing events that can be presented, 2) the probability that an event will occur, and 3) the sequential constraints imposed on the occurrence of an event (Wickens & Hollands, 1999). Hick (1952) and Hyman (1953) applied Information Theory to explain human performance in a choice response task. In doing so they established the Hick-Hyman Law, which states that the more information an event conveys, the longer humans take to process it. In applying the Hick-Hyman Law to active safety system design, it is foreseeable that drivers' response time to any one alert may increase as the number of active safety systems that generate alerts increases. This study quantifies the effect of increasing the amount of information conveyed by a haptic driver seat on drivers' response performance. Although various alert modalities have been proposed for the use in active safety systems, alerts solely presented through a haptic seat are an interest owing to results obtained in previous research (Fitch, Kiefer, Hankey, & Kleiner, 2007; Fitch, Kiefer, Kleiner, & Hankey, 2007; LeBlanc, et al., 2006; Lee, Hoffman, & Hayes, 2004).

METHOD

Participants

Twenty-four participants were equally selected from two age groups: a younger age group consisting of drivers between the ages of 18 and 25 years old, as well as an older age group consisting of drivers over the age of 65 years old. An equal number of males and females were selected from both age groups.

Apparatus

A 2002 Cadillac STS was used in this study. Video footage of the forward roadway, brake pedal, driver's face and the driver's hands placed on the steering wheel were recorded with cameras approximately 1 inch^3 in size that were indiscreetly mounted in the vehicle cabin. Video footage was multiplexed and digitally recorded at 29.97 Hz. Advancing through the video footage frame-by-frame post experiment allowed for precise determination of when a driving maneuver began and ended (with an error of ± 0.066 s). An audio recording also captured the participant's verbal responses.

Four inertial shaker tactors manufactured by InSeat Solutions, LLC. (www.inseatsolutions.com) were mounted in the driver seat (Figure 1). Two tactors were mounted along the front edge of the driver seat pan (seat bottom). Two more tactors were mounted in the back-left and back-right corners of the seat pan. Each tactor consisted of a small DC motor mounted on a metal plate. The motor rotated an eccentric cam shaft causing the motor-plate combination to vibrate. The integral dimensions of vibration frequency and intensity were controlled by varying the motor's speed, where faster speeds increased the vibration frequency and intensity. Here, the motor's speed was specified using a 50 percent duty cycle. Unfortunately, equipment to measure the actual frequency in which the cam made a complete revolution was not available. Discussion with InSeat Solutions, LLC. revealed that this specification was unknown to them as well. Furthermore, the tactors' nominal frequency changes when they are loaded by the driver's weight. Nevertheless, the tactors vibrated at an intensity that was clearly perceptible without being overly annoying (Fitch, Kleiner, Hankey, Dingus, & Winchester, 2009). It should be noted that not one driver failed to detect a single alert. Three vibrotactile patterns (pulse, dash, and double pulse) and three locations (front, back-right, and back-left) were used to communicate seven different alerts. The seven alerts, as well as descriptions of how they were generated, are listed in Table 1. The amount of time that the tactors vibrated for each pattern was controlled to be one second.

Procedure

Participants read and signed an Informed Consent form upon arriving at the Virginia Tech Transportation Institute. Participants removed their wallets and cell phones prior to sitting in the test vehicle. Participants drove the test vehicle at 32 km/h (20 mph) down the middle of the Virginia Smart Road. The experimenter presented one of seven haptic seat alerts. The participant's task was to correctly identify the presented haptic seat alert. This consisted of executing the proper manual response as fast as possible, and verbally identifying the alert. The number of possible alerts that could be presented to drivers was controlled at three levels. The first level consisted of just the forward collision warning (FCW) alert. The second level consisted of three possible alerts: an FCW alert, a right lane change warning (LCW) alert, or a left LCW alert. These three alerts all used the same vibrotactile pattern (five pulses). The third level included all seven alerts (Table 1). It is worth noting that alerts indicating a conflict with another vehicle (i.e., FCW and LCW alerts) consisted of five pulses, while alerts indicating a poorly controlled vehicle (CSW and LDW alerts) consisted of a dash-type vibration. The order in which participants were exposed to levels 1, 2, and 3 was counterbalanced. Participants were instructed to apply the brakes if an FCW, CSW, or IVW alert was presented (because they were intended to warn drivers to slow down), and to steer into the right lane if a left LCW or left LDW alert was presented (because they were intended to indicate a crash threat on the left side). Similarly, they were asked to steer into the left lane if a right LCW or right LDW alert was presented. Afterwards, participants verbally identified the alerts. Participants were asked to say “Car Ahead” when an FCW alert was presented, “Sharp Turn” when a CSW alert was presented, “Red Light” when an IVW alert was presented, “Car Right” when a right LCW alert was presented, “Car Left” when a left LCW alert was presented, “Drift Right” when a right LDW alert was presented, and “Drift Left” when a left LDW alert was presented. Verbal responses were scored based on meaning, and not specific terminology. For each condition, each type of alert was presented eight times. However, the first two trials for each alert were considered practice and were not analyzed.

Figure 1. Mounting of the four inertial shaker tactors. The two upper tactors in the seat back were not used

Table 1. Haptic Seat Alert Patterns

Alert	Haptic Pattern
Forward Collision Warning (FCW)	• Front-left and front-right tactors simultaneously activated five times (200 ms on, 50 ms off) (Pulse)
Curve Speed Warning (CSW)	• Front-left and front-right tactors simultaneously activated for one second (Dash)
Intersection Violation Warning (IVW)	• Front-left and front-right tactors simultaneously activated four times each (200 ms on, 50 ms off, 300 ms on, 200 off, 200 ms on, 50 ms off, 300 ms on, 50 off) (Double Pulse)
Left LCW	• Back-left tactor activated five times (200 ms on, 50 ms off) (Pulse)
Right LCW	• Back-right tactor activated five times (200 ms on, 50 ms off) (Pulse)
Left LDW	• Back-left tactor activated for one second (Dash Pattern)
Right LDW	• Back-right tactor activated for one second (Dash Pattern)

Independent Variables

This experiment consisted of a 2 (Age) x 2 (Gender) x 3 (#Alerts) mixed factors design. Both Age and Gender were between-subjects independent variables, while #Alerts was a within-subject independent variable.

Dependent Variables

Participants were instructed to perform a specific driving maneuver in response to each alert as fast as possible. The elapsed time from the alert to drivers' pressing the brake pedal comprised the response time measure for the FCW, CSW, and IVW alerts. The elapsed time from the alert to drivers' initiating a steering response into an adjacent lane comprised the response time measure for LCW and LDW alerts. Drivers' manual response accuracy was also scored. However, drivers were not penalized for pressing the brake pedal, or initially jerking the steering wheel in the wrong direction (where the vehicle's trajectory was not altered) prior to steering the vehicle into the correct lane in response to the lateral alerts. Furthermore, drivers were not penalized for jerking the steering wheel left or right (where the vehicle's trajectory was not altered) when pressing the brakes in response to the forward alerts. Participants' ability to correctly verbally identify the alerts after performing a driving maneuver was also scored.

RESULTS

Manual Response Accuracy

In general, drivers performed the correct maneuver in response to the haptic seat alerts with impressive accuracy (above 94 percent correct for each group of participants). Drivers made the correct manual response 100 percent of the time when one alert was presented, they made the correct response 99 percent of the time when three alerts were presented, and they made the correct response 97 percent of the time when seven alerts were presented (Figure 2a). A Cochran-Mantel-Haenszel (CMH) test revealed that these slight differences were statistically significant ($Q(2) = 8.9264$, $p = 0.0115$). Overall, there was a significant Age main effect ($\chi^2(1) = 21.9537$, $p < 0.0001$). Older drivers accurately identified 97 percent of the alerts, while younger drivers accurately identified 100 percent of the alerts. There was no significant difference in performance between males and females ($X(1) = 1.7212$, $p = 0.1895$). Females accurately identified 99 percent of the alerts, while males accurately identified 98 percent of the alerts.

Manual Response Time

Drivers' response times when making correct manual responses were analyzed using a 2 (Age) x 2 (Gender) x 3 (#Alerts) mixed factors ANOVA. The number of alerts was found to be a significant main effect ($F(2, 40) = 10.74$, $p = 0.0002$). Drivers' mean response time to just the FCW alert was 0.831 s (s.e. = 0.031 s), their mean response time when three alerts were presented was 0.847 s (s.e. = 0.017 s), while their mean response time when seven alerts were presented was 1.082 s (s.e. = 0.018 s) (Figure 2b). A Tukey multiple comparisons test revealed that drivers' mean response time to seven alerts was significantly different from their mean response time to one alert ($p = 0.0175$), and three alerts ($p = 0.0005$). A significant Age x #Alerts interaction was found (F(2, 40) = 4.55, $p = 0.0166$). It can be seen that younger drivers' response times did not increase as much as older drivers did when the number of alerts was increased. Drivers' mean brake response time (BRT) to just the FCW alert was of interest since the FCW alert was common to all three conditions. Figure 2c shows that drivers' mean BRT increased from 0.831 s, to 0.941 s, to 1.215 s as the number of alerts presented increased from one, to three, to seven. A significant difference in BRT was found (F(2, 40) = 14.12, $p < 0.0001$). A Tukey multiple comparisons test revealed that drivers' mean BRT to the FCW alert in the seven-alert condition was significantly different from their mean BRT to the FCW alert in the one-alert condition ($p < 0.0001$), and in the three-alert condition ($p = 0.0017$).

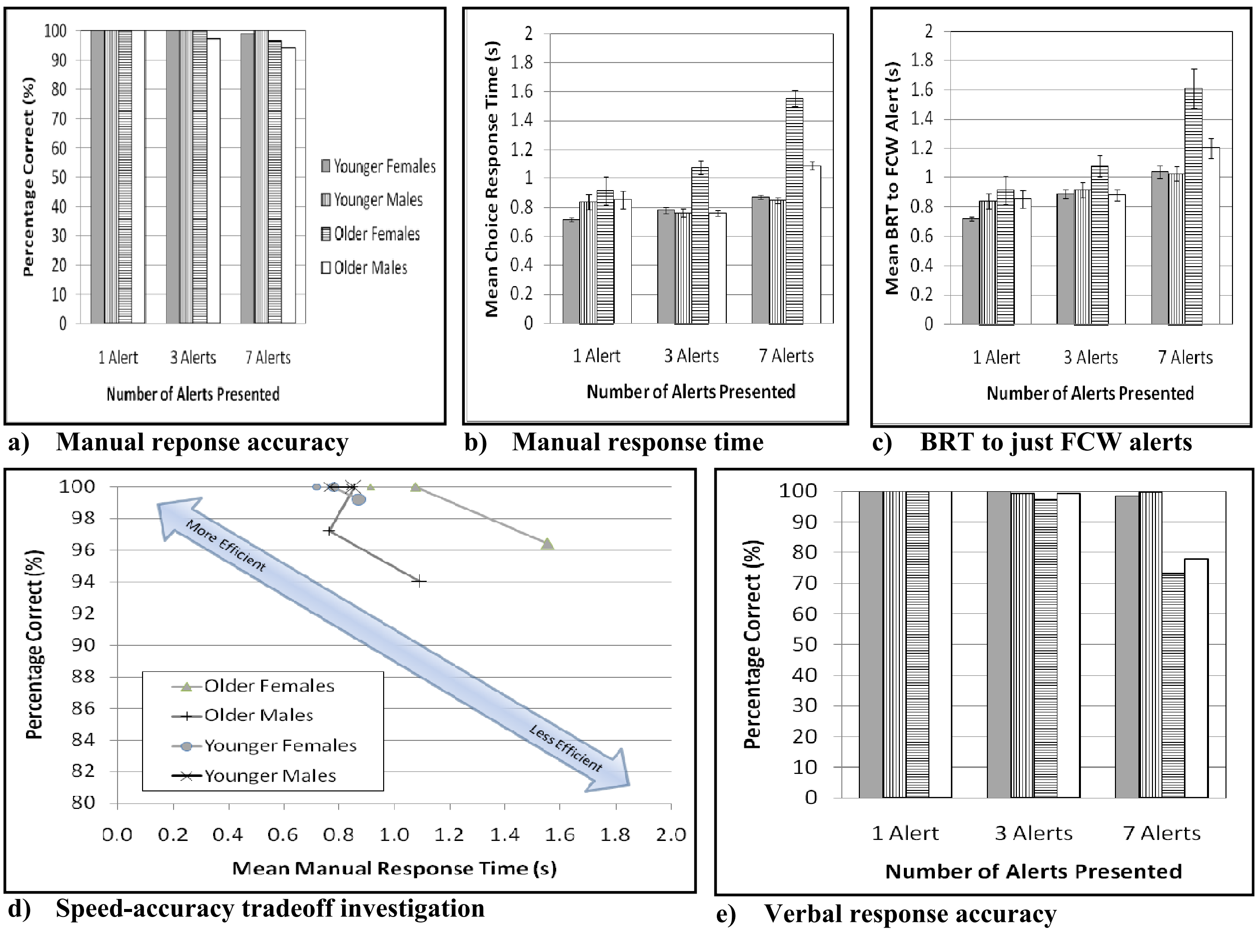

Figure 2. Drivers' response performance to haptic alerts. The legend shown in (a) applies to (b), (c), and (e)

Speed Accuracy Tradeoff

Response time and error rate represent two dimensions of the efficiency of processing information (Wickens & Hollands, 1999). Figure 2d shows that most drivers' performance moved from the top left of the graph (efficient information processing) down towards the bottom right of the graph (inefficient information processing) as the number of alerts increased from one to seven (the smallest symbol in a series represents the speed-accuracy data point associated with one alert, the next largest symbol represents the speed-accuracy data point associated with three alerts, and the largest symbol represents the speed-accuracy data point associated with seven alerts). This investigation shows that drivers had to use additional attentional resources to process the increased information conveyed by multiple alerts.

Verbal Response Accuracy

Drivers were generally accurate in verbally identifying the haptic seat alerts. Drivers accurately identified 100 percent of the alerts when only one alert was presented, 99 percent of the alerts when three alerts were presented, and 88 percent of the alerts when seven alerts were presented (Figure 2e). A CMH test revealed that the number of alerts presented had a significant effect on drivers' verbal response accuracy ($Q(2) = 67.457$, $p < 0.0001$). There was a significant Age main effect ($\chi^2(1) = 121.3536$, $p < 0.0001$). Older drivers accurately identified 84 percent of the alerts, while younger drivers accurately identified 99 percent of the alerts. It can be seen that the performance of younger drivers did not degrade as the number of alerts presented in a condition increased, while it did for older drivers. A Gender main effect was not found ($X(1) = 2.0872$, $p = 0.1485$). Females accurately identified 91 percent of the alerts, while males accurately identified 93 percent of the alerts.

DISCUSSION

This experiment was designed to quantify the effects of increasing the number of alerts presented to drivers through a haptic driver seat. In general, drivers were able to perform the correct driving response. This may be because of the intuitive design layout of the haptic seat. A strong stimulus-response compatibility was established by mapping vibrations along the front edge of the driver seat to pressing the brake pedal, and mapping vibrations along the side edges of the seat to steering in the opposite direction. The consistent use of three stimulus-response mappings appeared to allow drivers to effectively manage the manual response task by focusing on the location of the vibrations, rather than the specific vibration patterns. The use of unique tactors for each stimulus-response mapping may also have prevented confusion.

Drivers' manual response time to the alerts was found to significantly increase as the number of alerts presented increased. The same result was found when just considering drivers' BRTs to the FCW alert. Here, since the type of alert and manual response was consistent across trials, the response time increases stem from delays in information processing. Nevertheless, younger drivers' response times did not lengthen as much as older drivers. When considering the observed increases in manual response time, it is important to realize that a crash context was not provided in this study. Recall that Information Theory states that the amount of information conveyed by an alert is also dependent on its sequential constraints. It is possible that the presence of a developing crash threat may serve as a sequential constraint that an alert is about to generate.

Drivers' verbal response accuracy results showed that younger drivers were able to completely comprehend one, three, and seven alerts, while older drivers were only able to comprehend one and three alerts. It is interesting that although older drivers had difficulty comprehending seven alerts, they were still able to make the proper manual response with over 94 percent accuracy. These results suggest that haptic seat alerts may support drivers in making the correct avoidance maneuver, even when they do not fully understand the alerts' meaning.

Based on the findings from this study, a three-alert haptic driver seat approach is recommended providing the following design requirements are met:

1) *High Degree of Stimulus-Response Compatibility*. Alerts should be presented in an area mapped to the intended driving response maneuver. This will support drivers in making the appropriate driving response by attending to the alerts' location.

2) *Consideration for Drivers' Frame of Reference.* The location of the alerts should be in-line with the crash threat and drivers' frame of reference to support the direction of drivers' attention to the crash threat (Fitch, Kiefer, Kleiner, et al., 2007).

3) *Unique Tactors for Each Alert.* Alerts should be generated using unique tactors in order to improve alert discriminability.

4) *Large Distance between Tactors*. The tactors should be mounted as far apart as possible. Large separation distances are believed to facilitate clear perception of which tactors are vibrating (Fitch, Kiefer, Kleiner, et al., 2007). Use of seat shaker tactors addresses contact issues facing thin drivers.

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