Bypassing the Bottleneck: The Advantage of Fingertip Shear Feedback for Navigational Cues

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Multiple resource models suggest that there will be less interference between tasks that do not share the same processing resources or modalities. Most in-vehicle navigational systems rely on some type of auditory modality, which can be problematic in situations with high levels of background noise or when one is engaged in a secondary auditory task, such as talking on a cell phone. The haptic or tactile sensory modality may be an effective alternative for presenting important navigational information in a vehicle. The current study compared the effectiveness of auditory vs. tactile navigational instructions to the operator of a moving vehicle. Tactile shear cues were provided to the participants’ index fingers as they gripped the steering wheel. These tactile cues provided directional information that coincide with the direction of the applied skin displacement. In single task driving, participants made accurate lane changes in response to both auditory and tactile instructions. In dual-task driving, where participants conversed on a cell phone, participants were less accurate with auditory instructions than for tactile instructions. This suggests that in some instances, presenting information via the tactile modality may bypass the bottleneck described by multiple resource theories when there is competition for the same resources.

INTRODUCTION

According to Wickens’ multiple resource theory, there are multiple pools of resources available for processing information simultaneously in different sensory modalities (2002). When humans carry out more than one task requiring resources from the same pool, performance typically declines due to a processing bottleneck for that shared resource. Driving is a task that requires visual, spatial, and manual resources. Many in-vehicle navigational devices provide drivers with a visual representation of a roadway in order to indicate directional information; however, this can cause interference since driving is already requiring the use of visual resources.

One possible solution would be to present navigational information using a sensory modality that is not being occupied. In accordance with this notion, some in-vehicle navigational devices have also tried to utilize auditory commands to provide drivers with directional information. The problem, however, is that the auditory sensory modality can already be occupied by features of the driving environment, such as high levels of ambient noise from the roadway, or by secondary tasks, such as listening to the radio, talking to a passenger, or talking on a cell phone. For these reasons, presenting auditory navigational information might not be entirely effective.

Another way of potentially bypassing the bottleneck that comes from the overlap in processing resources would be to present information through the sense of touch or haptics. Several automobile companies have begun developing and even implementing in-vehicle systems that utilize haptic feedback for lane departure warnings, drowsy driver warnings, and blind spot monitoring (via torque feedback through the steering wheel, e.g., Pohl et al., 2007).

In the academic realm, there have been several studies that have shown the haptic sensory modality to be a fast and accurate method of receiving information while driving. For example, Ho, Reed, and Spence (2006) used vibrotactile warnings on a waste belt to indicate near front-end collisions, and they found that participants were able to brake faster and had larger safety margins with the vibrotactile device than without it. This corresponds nicely to one of the purported advantages of tactile communication, namely the rapid transmission of tactile information to the brain (Harrar & Harris, 2005; Ho & Spence, 2008). Other advantages include the relatively automatic manner in which tactile communication can alert (Geldard, 1960; Gilmer, 1961), as well as the seemingly natural mapping of directionality to body coordinates (Van Erp & Van Veen, 2001). In addition to these purported advantages of tactile communication, Ho and Spence (2008) reiterate the potential for tactile communication given that the tactile sensory modality is much less occupied by common driving behaviors than other modalities, such as visual and kinesthetic.

In terms of presenting navigational information, Van Erp and Van Veen (2004) tested a vibrotactile display on a driver’s seat—as opposed to a steering wheel—and compared visual and tactile navigational information as workload varied. They found that the tactile display reduced workload more than the visual display, especially in the high workload condition. They did not include an auditory condition nor did they focus on accuracy as much as reaction time and workload reduction.

Other researchers, such as Morrell and Wasilewski (2010) have also used a combination of vibrotactile and cam (pushing) mechanisms to heighten a driver’s sense of awareness to vehicles in his/her blind spot.

Researchers have also looked at providing haptic feedback directly through the steering wheel. This can be advantageous as the hands and fingertips are significantly more sensitive to haptic stimuli than the legs and torso (Jones & Sarter, 2008). Furthermore, presenting tactile feedback on the steering wheel has an advantage over steering wheel torque feedback in that the provided cues do not directly cause steering input. Regardless, the haptic feedback must be presented in an intuitive manner that does not interfere with normal steering activity.

Enriquez et al. (2001) pulsed pneumatic bladders located on the rim a steering wheel to draw a driver’s attention to an “abnormal” vehicle state that was visually displayed on gauge readouts. Their tactile feedback improved user’s reaction times. More closely related to our study, Kern et al. (2009) located small vibration actuators around the perimeter of a steering wheel to provide vibrotactile feedback. They provided their participants with vibration on the right or left side of the steering wheel to indicate a right or left lane change, respectively. However, their participants sometimes had difficulty interpreting these vibrotactile navigation cues. It is important
to note that these studies have not always utilized adequate dual-single task comparisons, nor have they been successful in presenting navigational information via haptic feedback on a steering wheel. This is important because it is not clear how effective haptic information is when combined with other sensory modalities, such as visual and auditory, using a device mounted to a steering wheel.

The current study tested the effectiveness of presenting navigational information through the haptic sensory modality, via fingertip shear feedback, while driving. Driving most often requires visual, spatial, and manual resources. In addition, driving also places demands on auditory resources because of high levels of ambient noise or secondary tasks, such as talking on a cell phone. According to the multiple resource theory, one could potentially bypass the bottleneck by engaging an unoccupied sensory modality, such as the haptic modality. Specifically, this study tested whether or not one could bypass the multiple resource bottleneck by using tactile shear feedback to deliver navigational instructions on a steering wheel.

**METHOD**

**Participants**

Nineteen students (13 men and 6 women) from a local university participated in this study for course credit. Participants ranged in age from 18 to 36 years old with an average age of 25.3 years. Participants reported having normal or corrected to normal vision and a valid driver's license at the time of the study.

**Stimuli and Apparatus**

A high-fidelity, fixed-base driving simulator was used in this study (Patrol Sim, manufactured by L-3 Communications). The simulator recreated a realistic driving environment through the use of dashboard instrumentation, steering wheel, and gas and brake pedals taken from a typical sedan with an automatic transmission.

Four, 6-minute driving scenarios were used. Each scenario consisted of a straight, three-lane, divided highway with no other vehicles. Vehicle speed was experimentally controlled and set to 55 mph. In two of the scenarios, participants received auditory navigation cues (i.e., "Left" or "Right" presented in a male voice), and in the other two scenarios, participants received tactile navigation cues indicating to change lanes to either the left or the right. For all scenarios, participants received 12 cues to the left and 12 cues to the right, either via the auditory or tactile modality.

A 2 (sensory modality) by 2 (workload) repeated measures design was used. The two levels of sensory modality were auditory and tactile. The two levels of workload were single and dual task. In the single task conditions, participants drove down the middle of the highway with no secondary task; in the dual task conditions, participants drove while having a naturalistic conversation with an experimenter over a cell phone. Drivers talked on the cell phone via a hands-free device, so that their two hands could remain on the steering wheel and associated tactile feedback devices.

A cell phone conversation was used because studies have shown that cell phone conversations can place significant demands on the auditory sensory modality (Strayer & Drews, 2007). The results, however, are not limited to cell phone conversations, but rather, they can be generalized to any feature of driving that sufficiently occupies the auditory sensory modality.

Figure 1: Haptic input and direction of skin displacement

The haptic input in this study was similar to the fingertip tangential skin displacement feedback used in Gleeson and Provancher (2010), shown in Figure 1, though the device was slightly modified to be mounted to a steering wheel (see Figure 2).

Figure 2: (left) Tactile feedback devices as haptic input mounted to the driving simulator’s steering wheel. The shear tactors face towards the dashboard. (right) User’s hand gripping the steering wheel. The index finger is retracted to more clearly show the tactile interface.

As indicated in Figure 1, with our tactile feedback device, the user places a finger onto a tactor (a rubber block about the size of a pencil eraser) that is placed in the center of a conical hole (labeled “Aperture” in Figure 1). The conical hole (with 12 mm inner diameter) helps center the user’s finger over the tactor and helps restrain the motion of the user’s finger. The sandpaper-like rubber tactor is from a ThinkPad laptop TrackPoint mouse interface.

The tactile stimulus comprises of a short motion of the tactor, tangential to the fingerpad, a short pause, followed by a slow return of the tactor to its centered position. The direction of the initial tactor motion corresponds to the cued direction. Generically, any direction in the plane of tactor motion could be indicated (Gleeson et al. 2010b), but the tactile feedback device design and stimuli used in this study were restricted to indicate left-right cues. These two tactile feedback devices rendered these cues by moving the tactor in a direction that is tangent to the steering wheel at the location of each tactile device. The tactor of each tactile device is moved in a manner that is consistent with portraying a clockwise or counter-
clockwise cue (in circumferential coordinates) indicating a right or left turn, respectively. The use of more than one tactile device made it clearer to participants that the tactile stimuli were indicating the direction to turn the steering wheel rather than an arbitrary spatial direction cue.

The devices’ tactors were moved simultaneously, with an outbound tactor motion of approximately 1 mm (measured as 1.05 ± 0.07 mm with a user’s finger in contact with the tactor, 1.31 ± 0.06 mm with no finger in contact) at approximately 4 mm/s, followed by a 0.3 sec. pause, then the tactor returned to its centered position. In the below experiments, the tactile stimulus (movement of a tactor followed by a return to center) was repeated twice, though a subsequent study in which only one tactile stimulus was used yielded identical results. Accuracy of over 95% has been found with tactile cues communicated in four directions with tactor displacements of 0.5 mm (Gleeson & Provancher, 2010). We have increased the tactor displacement to 1 mm, while reducing from four- to two-direction communication to ensure highly reliable tactile direction cues are communicated.

The current study uses only two tactile feedback devices (as opposed to many) that non-destructively attach to a standard car steering wheel and where mounted at approximately “10 o’clock” and “2 o’clock.” The tactile feedback devices were mounted to the steering wheel in a way that allowed participants to rest their index fingers on each tactor. The two tactile devices’ asymmetric design allowed for the user to easily interact with each device with each of their index fingers without affecting steering wheel grip of their remaining fingers. Right- and left-handed versions of the tactile feedback device were installed and used in this study. While driving, participants received instructions to move into either the left or right lane, and the instructions would either be auditory or tactile depending on the condition. All instructions were controlled by a simulation control computer, which also collected information about lane position for later calculation of accuracy.

Procedure

Before the study, participants were familiarized with the tactile device. Specifically, participants received 24 tactile cues (half left, half right) while they sat in the simulator but not driving. After each stimulus, they were required to verbally report which direction had been indicated. Participants were required to correctly identify the cued direction of all 24 tactile stimuli before proceeding with the experiment. This was done to ensure that the tactile cues were easily recognized when the participant’s full attention was available to judge the tactile cue, before proceeding with our cognitive study.

Participants drove four scenarios: single task auditory cues (A1), dual task auditory cues (A2), single task tactile cues (T1), and dual task tactile cues (T2). The order of the scenarios was counterbalanced. In all scenarios, participants were instructed to drive in the center lane of a 3-lane highway until they received a navigational instruction (auditory or tactile), at which time, they were to maneuver their vehicle into the lane indicated by the cue. After responding to each cue, participants were instructed to move back to the center lane and wait for the next instruction.

The main dependent measure in this study was accuracy, and the data were analyzed using a 2 (sensory modality: auditory vs. tactile) by 2 (workload: single vs. dual) repeated measures ANOVA.

RESULTS

Accuracy of navigation

In terms of accuracy of navigation, there was a main effect of sensory modality that indicated that tactile instructions led to more accurate lane changes than auditory instructions, F(1,18) = 33.3, p<0.01. There was also a main effect of workload indicating that participants were more accurate in single task conditions compared to dual task conditions, F(1,18) = 29.5, p<0.01. Finally, there was an interaction between sensory modality and workload, F(1,18) = 32.2, p<0.01. Planned comparisons revealed that accuracy significantly declined for the auditory conditions but not the tactile conditions in dual task driving (see Figure 3).

![Figure 3: Interaction of sensory modality and workload on accuracy. Error bars indicate 1 SEM](image)

It is noteworthy that accuracy was equivalent in single task driving for auditory and tactile conditions; in fact, participants were near ceiling levels in terms of accuracy for both types of navigational instructions in single task conditions.

DISCUSSION

In this study, tactile instructions led to more accurate lane changes overall, and single task conditions were more accurate than dual task conditions. In addition, accuracy declined from
single to dual task conditions but only for auditory instructions.

This finding is consistent with Wickens’ multiple resource theory (2008). Driving is a task that requires visual, spatial, and manual resource pools, and talking on a cell phone is a task that requires auditory, verbal, and vocal resource pools. Since both these traditional pools of resources are occupied, any additional navigational information presented either visually or auditorily would likely be missed. This study demonstrates that by using a different modality (i.e., haptic) whose resource pool is not being consumed one can potentially bypass the overlapping resource bottleneck predicted by the multiple resource theory. This also corresponds to research by Ho and Spence (2008) that has shown several advantages of tactile communication over other forms of communication, such as auditory and visual, presumably because the task of driving does not use as much of the tactile modality as it does these other modalities (Spence & Driver, 1997a; Spence & Driver, 1997b).

In addition to these theoretical implications, this research leads to potential real-world applications. Namely, it suggests that tactile feedback might be better suited for delivering navigational information when other resources (i.e., auditory) are occupied by high levels of ambient noise or secondary auditory tasks, such as listening to radio or talking on a cell phone.

Cell phone conversations were used in this study because we were interested in how participants would handle auditory and tactile navigational information when the auditory sensory modality was already being engaged. Because cell phone conversations consist of auditory, verbal, and vocal resources, they can be used to engage the auditory sensory modality in Wickens’ original multiple resource model. Other tasks, such as listening to passengers or the radio, as well as high levels of ambient noise can also engage the auditory resource pool. In fact, research has shown that out of all of these examples, cell phone conversations can cause severe interference with driving (Horrey & Wickens, 2006; Strayer, Drews, & Crouch, 2006; Strayer & Johnston, 2001). Thus, even if haptic feedback has the potential to bypass the bottleneck set forth by the multiple resource theory, one may still encounter more general bottlenecks from using a cell phone while driving, leading to negative consequences.

The current study also contributes to other studies using haptic feedback on a steering wheel. For example, in a recent study, Kern, Marshall, Hornecker, Rogers, and Schmidt (2009) presented participants with tactile feedback using a steering wheel-based design, and they found that participants were less accurate at making lane changes when given tactile feedback compared to auditory feedback. There are several reasons for why they might have found such different results from the current study. One major difference between the studies is the actual design of the tactile device. Kern et al. (2009) had one side of the steering wheel vibrate to indicate the direction of the intended lane change (i.e., left or right). Our device applied tactile feedback in the form of tangential skin displacement and has been highly effective in communicating direction cues (Gleeson et al 2010a, Gleeson & Provancher 2010). Another potential reason for the difference in findings could be the auditory output used. Kern et al. (2009) presented participants with beeps via headphones that would have canceled out all other ambient noise common to most roadways (e.g., engine brakes), and thus, their auditory condition might have had an advantage in terms of its clear presentation. Finally, another reason for the difference in results could be training effects with how tactile feedback was perceived. In the Kern et al. (2009) study, they tested for how accurately participants could perceive the tactile feedback only after the study; therefore, it is not clear whether or not participants slowly learned how to accurately perceive the tactile feedback over the course of the experiment. This could have led to less accurate lane changes for tactile feedback compared to auditory feedback, and the current study avoided this issue by ensuring that all participants could accurately perceive and interpret the tactile feedback before beginning the experiment.

Another more general consideration for the current study is our tactile feedback system. These two devices required participants to keep their index fingers on the tactors in order to receive the tactile feedback. While the devices were adjusted to each participant’s comfort and grip, we acknowledge that future in-vehicle implementations should consider a design with tactile feedback built into the rim of the steering wheel with many tactors placed around the entire perimeter of the steering wheel, thus allowing drivers to grip the steering wheel anywhere they would like, and allow the steering wheel to slide through their grip without presenting obstructions. Nonetheless, the design used in this study allowed us to test the efficacy and theoretical underpinnings of our device before moving on to a design fit for actual vehicle implementation.

In addition to adapting the design of the tactile devices, future research will test this type of tactile feedback in more complex driving conditions (i.e., with varying levels of traffic and in dynamic city settings), as well as to convey other types of information.

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REFERENCES


