The Value of Multimodal Feedback in Automotive User Interfaces

Literature Review

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Both audio and tactile feedback should be included to achieve the most effective implementation.

1. Executive Summary

Many automobile manufacturers are beginning to utilize touchscreen technology in their vehicles. Touchscreens offer vast benefits for manufacturers and consumers alike in terms of flexibility and ease of use. However, touchscreens have the potential to be visually distracting. Guidelines are currently in place from the NHTSA and the SAE for maximum task and glance times. Multimodal feedback—audio and tactile feedback—can help mitigate the potential danger of touchscreens in cars by reducing glance times and improving reaction times to in-vehicle tasks. Moreover, users enjoy using interfaces with multimodal feedback more than visual feedback alone. This review includes a number of current studies exploring driver distraction, multimodal feedback in touchscreens, and multimodal feedback in vehicles. These studies show that multimodal feedback is an essential component for a safe, effective, and enjoyable in-vehicle touchscreen system.

Acura RLX dual touchscreen — one used as a display and one touch screen to control audio, navigation, and climate controls.

The key points of this review include:

- Touchscreens without multimodal feedback have the potential to be unsafe in automobiles.
- Adding multimodal feedback to a touchscreen interface makes touchscreens more accessible in visually demanding or low-vision situations.
- Multimodal feedback improves touchscreen task performance.
- Users rate multimodal feedback interfaces higher on subjective scales than strictly visual interfaces.
- In vehicle interfaces, audio feedback may be masked by high levels of ambient noise. Tactile feedback may be masked by high levels of ambient vibration. Providing redundant information in multiple modalities allows the user to adapt cognitive resources to the changing context.
- Both audio and tactile feedback should be included to achieve the most effective implementation.
- Quality constraints exist on both audio and tactile feedback. More research is recommended to further specify parameters for strength, effect design, and latency tolerance in realistic driving contexts.

This review spans the current research on the topic of multimodal feedback and has important implications for automobile manufacturers looking to include a touchscreen interface in future vehicle models.

Adding multimodal feedback to a touchscreen interface makes touchscreens more accessible in visually demanding or low-vision situations.

2. Introduction

Touchscreens are ubiquitous in technology today, and are becoming more frequently integrated into automotive interfaces. There are many advantages to using touchscreen systems in automotive applications. For example, buttons can be displayed directly on the screen, preventing the need for physical keys and saving space, weight, and wear and tear. Replacing a static button-and-knob interface with a touchscreen creates the opportunity to place more functions at the driver's fingertips. Many sources of information and options for vehicle and environmental control can appear in the same space. The radio, climate controls, and navigation system can all inhabit one screen beside the driver. Moreover, with the explosive growth of touchscreen appliances and devices in the marketplace, consumers are coming to expect touch interfaces in modern automotive technology. Once seen as a luxury feature, touchscreens are becoming incorporated in more mid- and economy-level vehicle models.

Cadillac CUE blends first-of-its-kind technology with highly intelligent design, bringing the intuitive control of smart phones and tablets safely to the road.

However, 25 years ago, touchscreens were reported to be unsafe in automotive vehicles because they required too many eye fixations, too much hand-eye-finger coordination, and too much touch accuracy on the part of the driver (Zwahlen, Adams, & DeBals, 1988). In other words, touchscreens were deemed too distracting to be safe in cars. While touchscreen technology has come a long way since 1988, the problem of visual interaction still remains.

Touchscreens are visual devices, and driving is a visual task. Any in-vehicle system has the potential to be dangerously distracting, but touchscreens, with their intricate user interfaces, are particularly diverting.

Using multimodal feedback, such as sound or vibration, to confirm the actions of drivers can help make touchscreens less visual. This review argues that multimodal feedback is an essential component for touchscreen in-vehicle systems. Multimodal feedback makes touchscreens less visually distracting without detracting from their ease of use and flexible nature, making cars safer without making them less enjoyable.

3. Touchscreens in Cars

Touchscreens in cars have the potential to be overly distracting. Driving and manipulating a touchscreen both require the visual attention of the driver. This is a fundamental problem. Decades of studies of dual-task interference show that simultaneously attempting multiple similar tasks greatly interferes with the performance of each individual task (Hirst & Kalmar, 1987; Navon & Miller, 1987; Pashler, 1994; C. D. Wickens, 2002; C. Wickens, 1991). Moreover, studies have shown that during driving, eye glances lasting more than 2 seconds significantly increase the driver's crash risk (Klauer, Dingus, Neale, Sudweeks, & Ramsey, 2006). The National Highway Traffic Safety Administration has recommended that glances towards an in-vehicle system not exceed 2 seconds (NHTSA-2010-0053), and SAE International's guidelines state that no one task on an in-vehicle system should exceed 15 seconds (SAE J2364).

As natural as current touchscreens are to use, the technology still has not overcome its heavy reliance on visual attention. Studies of driving simulations show that drivers interacting with in-vehicle systems pay less visual attention to the road (Horrey, Wickens, & Consalus, 2006) and perform similarly to drivers using temporary blinders that occlude their vision from the road (Tsimhoni & Green, 2001). Figure 1 illustrates how even the basic task of maintaining lateral position on the road becomes more difficult when the driver is completing a secondary in-vehicle task. In this study, Tsimhoni & Green (2001) showed that variability in lateral position increased by 80% when drivers were asked to complete a map-reading task.

The CUE recieved a Connected Car of the Year award that honor vehicles with technology that strike the right balance of safety, convenience, and infotainment.

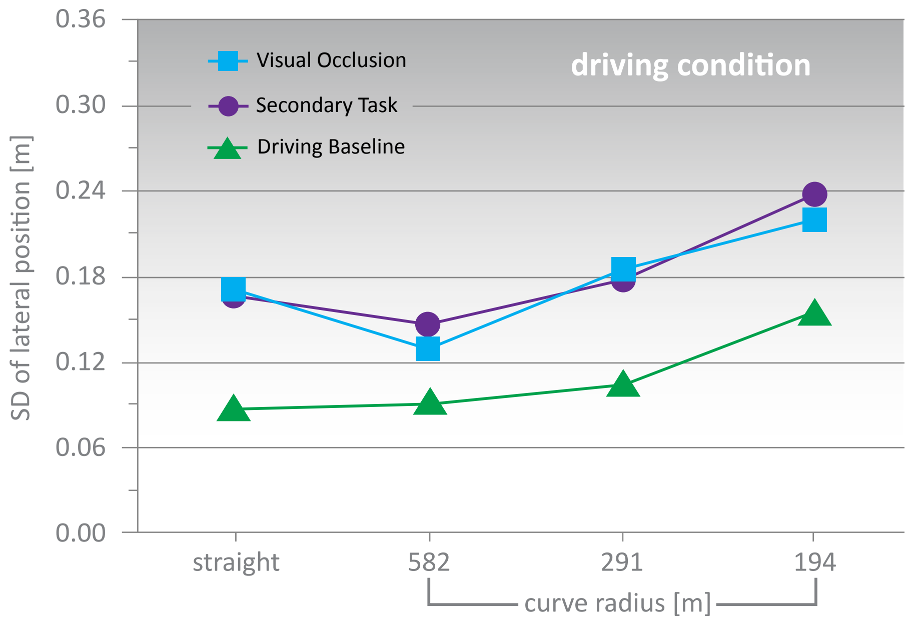

Figure 1. The effect of curvature on the variability of lane keeping. Performing a secondary task results in a higher standard deviation of lateral position. Performance of participants in the secondary task condition is almost identical to that of participants in the voluntary visual occlusion condition. Adapted from Tsimhoni & Green (2001).

Driving is a visually demanding task. Therefore, in-vehicle systems should be designed to use complementary modalities for feedback.

This effect is not impacted by the complexity of the task. In a series of driving simulations, Engström, Johansson, & Östlund (2005) showed that increased cognitive load did not result in more erratic driving. Therefore the dangerous aspect of the touchscreen in-vehicle systems is not the task being performed; rather, it is the visual component of the interface itself.

In American culture, the dangers of distracted driving are well-recognized. For example, numerous campaigns have been launched to encourage drivers to abstain from interacting with mobile phones while on the road (e.g. "Texting and Driving Prevention.," 2011, "Texting and Driving Safety, No Texting and Driving," 2013), and 11 states, including the District of Columbia and the Virgin Islands, prohibit drivers from using hand-held mobile phones while driving ("State Laws: Digest of Distracted Driving Laws," 2012).

These serious criticisms may be aimed at touchscreens, but the implications of these studies, campaigns, and regulations are broader than that. The same scrutiny could be placed over anything potentially distracting in cars, even the ubiquitous radio knobs and buttons. The automotive industry needs to find a solution to make in-vehicle systems less visually distracting without sacrificing quality and intuitive interaction. Multimodal feedback represents a viable and practical solution to this problem.

4. What is Multimodal Feedback?

Multimodal feedback in the context of touchscreens includes audio feedback, tactile feedback, and any other modality beyond visual feedback. Audio and tactile feedback have been utilized in touchscreen devices to give confirmation and make the digital buttons seem more like physical buttons (Koskinen, Kaaresoja, & Laitinen, 2008; Poupyrev & Maruyama, 2003).

These technologies make touchscreens less visually-demanding and have been utilized to make touchscreens more accessible to people with visual disabilities or impairments (Guerreiro, Lagoa, Nicolau, Gonalves, & Jorge, 2008; Kane, Bigham, & Wobbrock, 2008).

Multimodal feedback is important for touchscreens in automobiles. Performing two visual tasks is difficult (if not dangerous), but performing visual and non-visual task is less burdensome. Multiple resource theory states that human operators have multiple, limited resources, and performance of tasks degrades when any particular resource is overtaxed but not when simultaneous tasks involve different resources (Wickens, 2002). For example, speaking with a colleague does not generally impair walking. However, "texting" and walking is widely regarded as a dangerous habit (Greenberg & Tridle, 2013; Thompson, Rivara, Ayyagari, & Ebel, 2012). Holding a conversation is a verbal task involving the auditory system and therefore should not interfere with the visual and physical task of walking. Texting, on the other hand, is not only verbal but very visual, which would impinge on the visual component of walking.

Following this theory, adding multimodal feedback to a touchscreen makes the user interface more accessible in visually demanding conditions and less damaging to other visual tasks. Driving is a visually demanding task. Therefore, in-vehicle systems should be designed to use complementary modalities for feedback.

Multimodal feedback makes touchscreens less visually distracting without detracting from their ease of use and flexible nature, making cars safer without making them less enjoyable.

5. Benefits of Multimodal Feedback

Present research shows that multimodal feedback is both objectively and subjectively beneficial to the user.

Multimodal feedback has been shown to improve task performance. In a comprehensive meta-analysis which included data from over 40 studies, Burke et al. (2006) showed that adding an additional modality to visual feedback improved task improved performance scores and lowered reaction times. Multimodal feedback has been shown to enhance task performance with mobile phones on a subway train (Hoggan, Crossan, Brewster, & Kaaresoja, 2009), touchscreens in a driving simulation (Lee & Spence, 2008), and robotic surgery (Bethea et al., 2004). Figure 2, from Lee & Spence (2008), shows the mean reaction times to an in-vehicle touchscreen task. Reaction times were significantly reduced in the multimodal feedback condition. These studies indicate that multimodal feedback may be especially ideal for task performance in a complicated environment like driving in traffic.

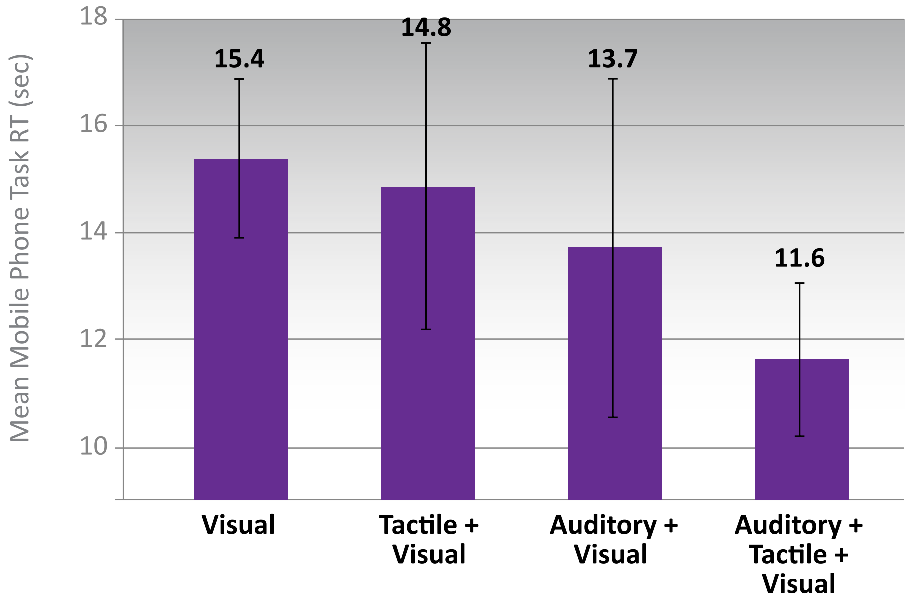

Figure 2. Mean reaction times on the in-vehicle screen task. Participants responded significantly more rapidly to audio-tactile-visual feedback than to visual-only ($p<0.05$). Adapted from Lee & Spence (2008).

Research indicates that users also enjoy multimodal feedback. Studies have shown that users prefer multimodal feedback over visual feedback alone in touchscreens in automobiles (Pitts, Skrypchuk, Wellings, Attridge, & Williams, 2012; Pitts, Williams, Wellings, & Attridge, 2009) and in smartphones (Hoggan, Brewster, & Johnston, 2008; Koskinen et al., 2008). Users report that multimodal feedback enhances user experience, makes them feel more confident in their button presses (Pitts, Skrypchuk, et al., 2012; Pitts et al., 2009), and makes the on-screen buttons feel more like real buttons (Koskinen et al., 2008). Figures 3a-c, from Pitts et al. (2009), illustrate the user preference for multimodal feedback. Figure 3a shows that the mean hedonic ratings are significantly greater for multimodal feedback than for visual feedback alone, and Figure 3b shows the same for confidence ratings. Figure 3c illustrates users' preference for audio-tactile-visual feedback over all other forms of feedback. Audio-tactile-visual feedback was most often ranked as users' most preferred form of feedback and was never ranked as users' least preferred form of feedback. These figures show that multimodal feedback is more enjoyable for users than a simple visual feedback.

Studies have shown that users prefer multimodal feedback over visual feedback alone in touchscreens in automobiles.

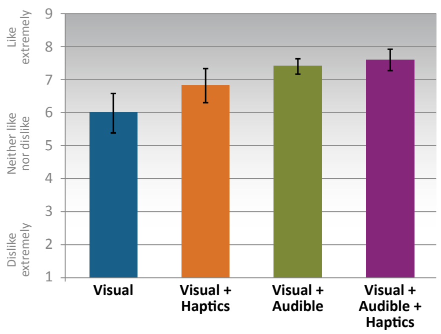

Figure 3a. Mean hedonic ratings for each feedback combination. Mean hedonic ratings for visual + audible + haptic feedback are significantly higher than for visual feedback along (p<0.0001). Adapted from Pitts et al. (2009).

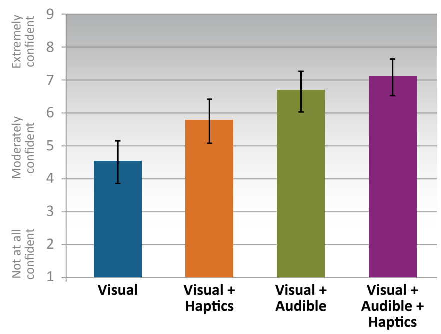

Figure 3b. Mean confidence ratings for each feedback combination. Mean confidence ratings for visual + audible + haptic feedback are significantly higher than for visual feedback alone (p < 0.0001). Adapted from Pitts et al. (2009).

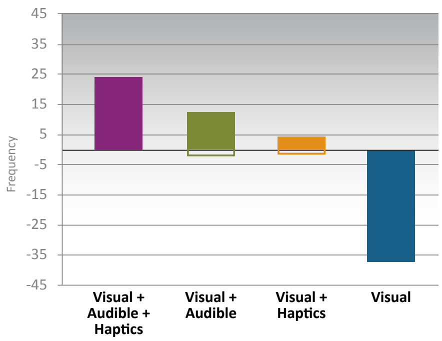

Figure 3c. Histogram of most/least preferred feedback state. Frequency of most-preferred is shown as positive, while frequency of less-preferred isshown as negative. The visual + audible + haptic condition has the highest frequency of most-preferred, while the visual condition has the highest frequency of least-preferred. Adapted from Pitts et al. (2009).

Multimodal feedback has even been shown to be more effective at the neurological level. A technical study by Antons, Arndt, Seebode, Schleicher, & Möller (2013) measured electrical activity in the brain using electroencephalogram (EEG) technology in response to audio, haptic, and visual feedback in a mobile device. They determined that that combined audio-haptic-visual feedback elicited a larger P300 electric event-related potential (ERP) than visual feedback alone. ERP events are spikes in neural electric activity associated with certain mental states, feelings, or behaviors. The P300 neural component correlates with attention, and an increased P300 effect is associated with an increase in attention (Donchin & Coles, 1988; Johnson, 1988), especially to self-relevant stimuli (Gray, Ambady, Lowenthal, & Deldin, 2004). Figure 4 shows the grand average ERPs recorded in the study. The P300 peak of the ERP is highest for the audio-tactile-visual feedback condition. This means that users pay more attention to multimodal stimuli and may even respond to it more personally than visual feedback alone.

Integrating multimodal feedback into in-vehicle systems has the potential to enable automobile manufacturers to maintain the intuitive and psychologically satisfying nature of touchscreens while making the technology less visually taxing.

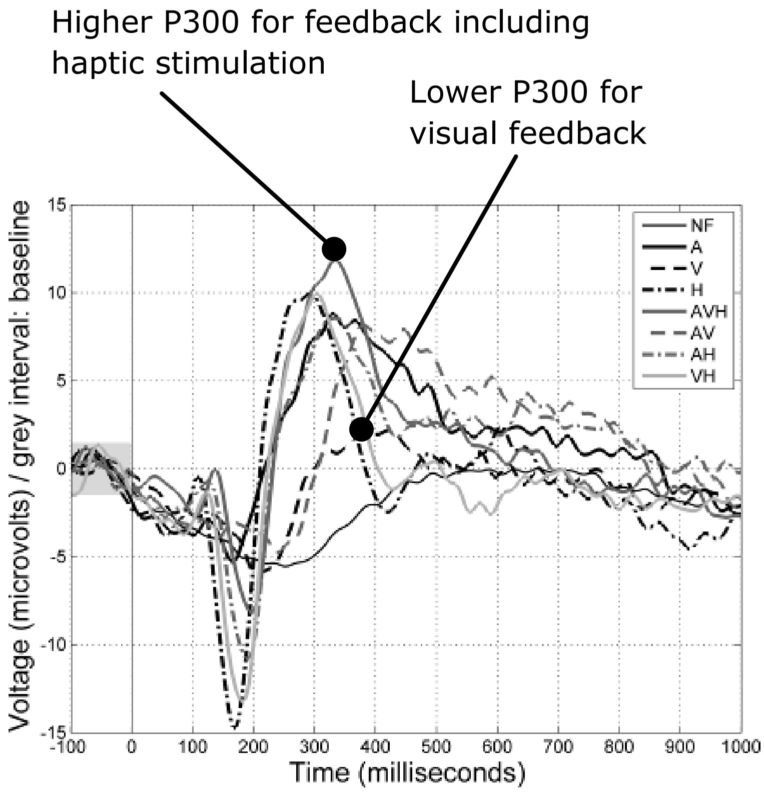

Figure 4. Grand average ERPs for all types of feedback tested - no feedback, audio feedback only, visual feedback only, haptic feedback only, audio-visual-haptic, audio-visual, audio-haptic, and visual-haptic. From Antons et al. (2013).

Integrating multimodal feedback into in-vehicle systems has the potential to enable automobile manufacturers to maintain the intuitive and psychologically satisfying nature of touchscreens while making the technology less visually taxing.

6. Audio vs. Tactile — Which Modality When?

Hoggan et al. (2009) discusses the advantages of tactile and audio feedback at different levels of ambient noise and vibration. The study shows that audio feedback of 68dB(A) becomes ineffective at high environmental noise levels (> 94 – 96dB) (see Figure 5). To put this is the context of the automobile, in-vehicle noise levels have been measured on a variety of cars to be between 66 and 76dB at approximately 80 mph (Schwoerer, 2009), and midtown Manhattan (New York City) traffic is reported to be between 70 and 85dB ("A Guide to New York City's Noise Code," 2011). However, the majority of drivers also listen to music (Dibben & Williamson, 2007). If a driver were trying to drown out the sound of rush-hour traffic, one can easily see how in-vehicle sound levels could approach 90dB.

The human auditory system is quite adept at isolating a single sound source from a complex field (e.g. the so-called "cocktail party effect" (Bronkhorst, 2000). However, Narayan et al. (2007) discovered a sharp decline in the ability to discriminate between auditory stimuli when background noises were too numerous and complex. It is not yet known how synchronous tactile feedback might influence audio discrimination and attention processes in such complex auditory environments, such as realistic driving contexts.

The same study by Hoggan et al. (2009) shows that tactile feedback at 250 Hz becomes ineffective at high environmental vibration levels (> 9.18 – 9.45 g/s) (see Figure 5). While these intense vibrations were experienced on a subway train and not in a car, ambient vibration is a frequent occurrence in automobiles, and the fact that tactile feedback may be masked under certain conditions should be considered.

Moreover, the meta-analysis from Burke et al. (2006) shows that tactile feedback in addition to visual feedback was more effective when users were performing multiple tasks in mentally demanding conditions, while visual-auditory feedback was most effective when users were performing a single task in less mentally demanding conditions.

However, as discussed earlier, multiple driving-simulation studies (Pitts, Skrypchuk, et al., 2012; Pitts et al., 2009. See Table 1 in Appendix.) show that users have a preference for combined audio and tactile feedback over audio or tactile feedback alone. Moreover, Lee & Spence (2008) show that reaction times for a car avoidance task significantly improved for audio-tactile-visual feedback over visual

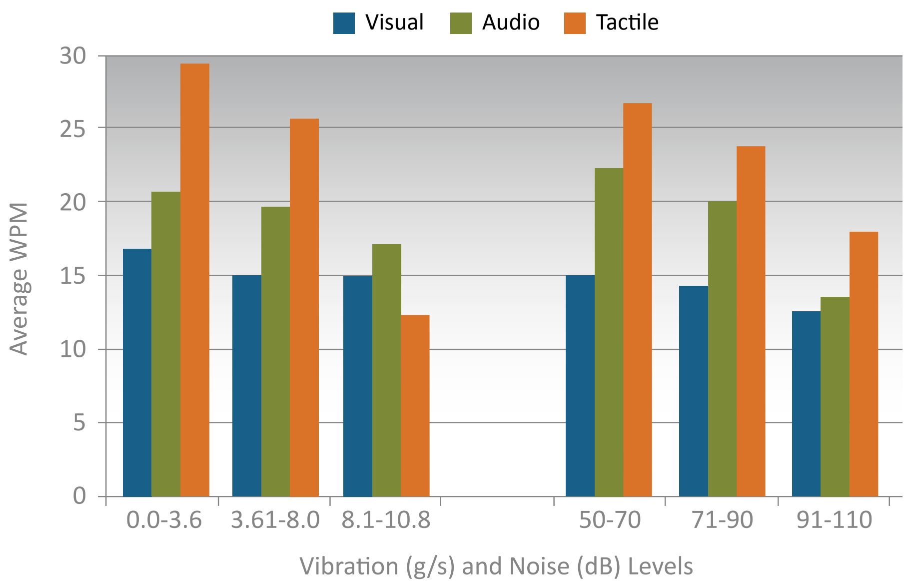

Figure 5. Mean words per minute for each set of vibration and noise levels. For high ambient noise levels (91-110 dB), the average count of words per minute in the audio feedback condition is approximately the same as in the visual feedback condition. For high ambient vibration levels (8.1-10.8 g/s), the average count of words per minute in the tactile feedback condition is approximately the same as in the visual feedback condition. Adapted from Hoggan et al. (2009).

feedback alone, but reaction times did not significantly improve for audio-visual or tactile-visual feedback (see Figure 6). Therefore, while audio and tactile feedback each has benefits, they should be combined for the most impactful results. Moreover, delivering the user feedback in multiple modalities will allow the driver to adapt cognitive resources to the changing context.

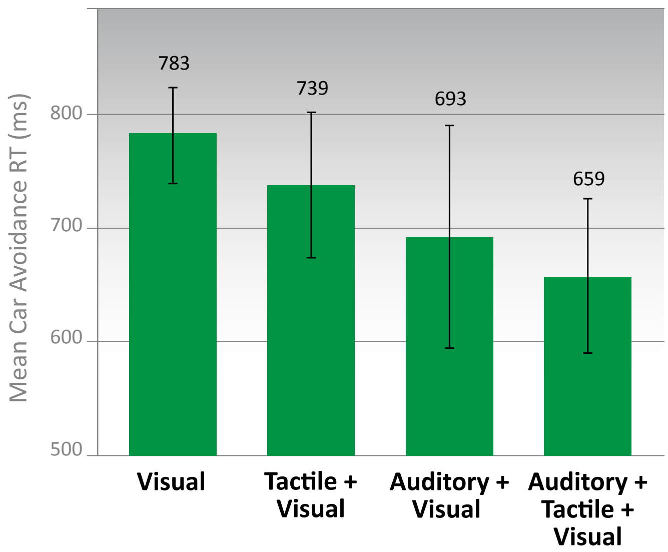

Figure 6. Mean response time in trials where participants successfully avoided an approaching car. Response times were significantly reduced in the audio-tactile-visual condition with respect to the visual-only condition ($p<0.05$). Adapted from Lee & Spence (2008).

7. Conclusions and Recommendations

The difficult nature of in-vehicle systems should not be surprising. Decades of studies of dual-task interference show that simultaneously attempting multiple similar tasks greatly interferes with the performance of each individual task (Pashler, 1994; Navon & Miller, 1987; Hirst & Kalmar, 1987; Wickens, 1991; Wickens, 2002). Touchscreens in cars are problematic because they are a primarily visual tool, and driving is a primarily visual task. Multimodal feedback can mitigate this issue by adding a non-visual dimension to the touchscreen.

7.1 Limits of Multimodal Feedback

In the meta-analysis by Burke et al. (2006) discussed earlier, multimodal feedback improved performance scores and reaction times, but it did not reduce error rates. Moreover, even though multimodal feedback can improve driving performance with respect to visual feedback alone, adding an in-vehicle system task to a driving simulation still detracts from driving performance (Lee & Spence, 2008. See Table 1 in Appendix). In terms of usability, touchscreens are an improvement over traditional knob-and-button interfaces (Bach, Jæger, Skov, & Thomassen, 2008), but that doesn't mean that interacting with a touchscreen while driving is safer than being undistracted.

7.2 Quality Constraints

Automobile manufacturers should keep quality constraints in mind. The just-noticeable threshold for audio-tactile asynchrony is small—around 24ms (± 2.2ms std error) (Adelstein, Begault, Anderson, & Wenzel, 2003), meaning that audio feedback needs to be delivered at a latency of less than 26.2ms to be perceived as simultaneous with the visual feedback. Users notice and dislike tactile feedback with a latency of more than 50 to 60ms (Jay & Hubbold, 2005; Okamoto, Konyo, Saga, & Tadokoro, 2009), and users respond more quickly to "strong double" multimodal feedback than weaker multimodal feedback (Lee & Spence, 2008). And the intensity of tactile feedback modulates the just-noticeable latency threshold (Rank, Shi, J. Müller, & Hirche, 2010). An effective multimodal feedback system should be sufficiently low-latency and intense. More research needs to be done to explore the optimal latency, strength, and effect design for tactile feedback in automobiles.

7.3 Recommendations

This review recommends that all automobile manufacturers include multimodal feedback in in-vehicle touchscreen systems. Multimodal feedback makes these screens safer, easier, and more appealing to use. Auto manufacturers should work to develop a multimodal feedback system with sufficiently high-quality tactile and audio feedback to create the most optimal system designs.

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APPENDIX

Table 1: Current Studies in Multimodal Feedback & Driving Interference

Topic: Driving Interference

CITATION	DESCRIPTION OF TASK	FINDINGS
Bach et al. (2008)	Basic interaction tasks with three different interfaces-- a traditional button radio, a touchscreen, and a gesture interface-- during controlled and simulated driving conditions. N = 16.	Participants exhibited fewer eye glances toward the in-vehicle system in the gesture condition and the lowest task completion times in the touchscreen condition. Significantly fewer driving errors were made in both the touchscreen and gesture conditions than in the traditional radio condition. Tactile interaction (the traditional radio condition) resulted in significantly more lateral control errors than touch and gesture (Tukey HSD post hoc test, $p < 0.01$). Time spent on each task was significantly different between the tactile, touch, and gesture systems (ANOVA, $F(2,45) = 65.53$, $p < 0.0001$). Number of glances away from the road was significantly different between the tactile, touch, and gesture systems (ANOVA, $F(2,45) = 38.4$, $p < 0.0001$).
Horrey, Wickens, & Consalus (2006)	Reading and voice dialing task using an LCD during a driving simulation with wind turbulence. Experiment 1: N = 8. Experiment 2: N = 11.	More demanding in-vehicle technology tasks led to less visual scanning of the road. In Experiment 1, percent of dwell time on the outside world decreased as in-vehicle task bandwidth increased (ANOVA, $F(2,14) = 33.6$, $p < 0.01$). In Experiment 2, increasing IVT complexity significantly decreased dwell time on the outside world (by 18% on average, ANOVA, $F(1,10) = 188.90$, $p < 0.01$). Increasing IVT complexity also increased variability in lane keeping (ANOVA, $F(1,10) = 26.0$, $p < 0.01$).
Tsimhoni & Green (2001)	Reading a map on a computer monitor during a driving simulation with straight and curved sections. N = 16.	Adding a secondary task degraded driving performance, and greater driving difficulty led to shorter glance times towards the in-vehicle system. Performing a secondary in-vehicle task increased lane departures from zero to approximately 1 departure per minute, and variability in lateral position increased by 80%. Mean glance duration decreased as road curves became sharper (1.8s on straight sections to 1.2s on 194m radius curves, $p < 0.0001$) and total glances duration decreased as road curves became sharper ($p < 0.001$).
Engström et al. (2005)	Performing a visual task on a touchscreen mounted next to the driver and an audio task while driving on a simulated motorway. N = 48.	Increased visual load degraded driving performance, but increased cognitive load did not have the same effect. Performance of the visual task resulted in increased variance of lateral position. The main effect of visual task conditions was significant ($F(3,71) = 10.3$, $p < 0.05$). However, the cognitive load task reduced variance in lateral position ($F(3,74) = 8.4$, $p < 0.05$).

Table 1 continued

Topic: Multimodal Feedback

CITATION	DESCRIPTION OF TASK	FINDINGS
Hoggan et al. (2009)	Typing phrases on a smartphone with an on-screen keyboard with either tactile feedback, audio feedback, or visual feedback only while traveling on a subway train. N = 12.	Tactile and audio feedback both improved user performance when compared to visual feedback only. Audio feedback became ineffective at high levels of ambient noise, and tactile feedback became ineffective at high levels of ambient vibration. Significantly more keystrokes per character for audio feedback as compared to tactile feedback when ambient audio was very loud (91-110 dB) ($F(2,22) = 11.1$, $p < 0.001$). Significantly more keystrokes per character ($F(2,22) = 8.22$, $p < 0.001$) and less words per minute ($F(2,22) = 4.9$, $p < 0.001$) for tactile feedback as compared with audio feedback when ambient vibration was very high (8.1-10.8 g/s). Significantly less words per minute at high ambient noise levels with audio and visual feedback than with tactile feedback ($F(2,22) = 2.91$, $p < 0.001$).
Hoggan et al. (2008)	Typing phrases on a smartphone with a physical keyboard, an on-screen keyboard with tactile feedback, or an on-screen keyboard without tactile feedback. Experiment 1: N = 12. Experiment 2: N = 12.	Tactile feedback improved user interaction with on-screen keyboards. In Experiment 1, a significantly higher number of phrases was entered correctly on both the physical keyboard and tactile touchscreen than on the standard touchscreen (with visual feedback only) (Tukey's post-hoc pairwise comparisons, $p = 0.05$). Key strokes per character were significantly higher when typing on tactile touchscreen than the physical or standard touchscreen keyboards (with visual feedback only) (Tukey's post-hoc pairwise comparisons, $p = 0.05$). And the time taken to enter phrases on the physical keyboard and tactile touchscreen were significantly lower than in the standard touchscreen keyboard (with visual feedback only) (Tukey HSD test, $p = 0.05$). In Experiment 2, significantly more phrases were entered correctly on the physical keyboard, PDA with two C2 actuators, and tactile touchscreen than on the standard touchscreen (with visual feedback only) (post-hoc Tukey test, $p = 0.05$). Key strokes per character were significantly higher when typing on tactile touchscreen than the physical keyboard, PDA with two C2 actuators, or standard touchscreen (with visual feedback only) (Tukey's pairwise comparison, $p = 0.05$), but there was no statistically significant difference in key strokes per character between the physical keyboard and the PDA with C2 actuators. And the time per phrase entered on the PDA with C2 actuators was significantly lower than on the tactile touchscreen and standard touchscreen (with visual feedback only) (Tukey test, $p = 0.05$).

Table 1 continued

Topic: Multimodal Feedback & Driving

CITATION	DESCRIPTION OF TASK	FINDINGS
Lee & Spence (2008)	Menu navigation and typing tasks during a driving simulation performed on a touch screen in-vehicle system with audio, tactile, audio and tactile, or just visual feedback. Intensity of tactile feedback was also varied. Experiment 1: N = 8. Experiment 2: N = 14.	Performance in driving task was significantly improved in the multimodal feedback condition over visual feedback alone. Reaction times in the touch screen task were improved in the double-strong tactile feedback condition with respect to the single-weak feedback condition. In Experiment 1, Participants responded significantly more rapidly in the car-avoidance task when the in-vehicle task involved trimodal feedback (audio-tactile-visual) than when given just visual feedback (an average of 124 ms faster, 1-tailed pairwise comparison test, $p < 0.05$). Participants also responded significantly more rapidly to the in-vehicle task when it involved trimodal feedback (audio-tactile-visual) than when given just visual feedback (1-tailed pairwise comparison test, $p < 0.05$). In Experiment 2, the effect of multimodal feedback (weak single vibration, weak double vibration, strong single vibration, double strong vibration) had a statistically significant effect on participants' mean reaction on the touch screen task ($F(1,13) = 12.69$, $p < 0.005$).
Pitts et al. (2009)	Menu navigation and button press tasks during a driving simulation performed on a touch screen in-vehicle system with audio, tactile, audio and tactile, or just visual feedback. N = 40.	Combined audio and tactile feedback was preferred over audio, tactile, or strictly visual feedback. Hedonic ratings improved from the "visual only" condition with the addition of audio and tactile feedback (Wilcoxon Signed Rank pairwise text, $p < 0.0001$). Mean score for visual feedback only = 6.00 (SD = 1.91). Mean score for visual-audio-tactile condition = 7.60 (SD = 1.08). Confidence in button press improved from the "visual only" condition with the addition of audio and tactile feedback (Wilcoxon Signed Rank pairwise text, $p < 0.0001$). Mean score for visual feedback only = 4.48 (SD = 2.06). Mean score for visual-audio-tactile condition = 7.00 (SD = 1.80).

Table 1 continued

Topic: Multimodal Feedback & Driving

CITATION	DESCRIPTION OF TASK	FINDINGS
Pitts, Burnett, Williams, & Wellings (2010)	Search-and-select touch screen task during a driving simulation performed on a screen with either tactile feedback or visual feedback only. N = 36.	Tactile feedback improved task performance when visual feedback was delayed or removed and reduced the amount of time that participants spent looking at the in-vehicle system. Tactile feedback also elicited improved experience and higher confidence ratings. When tactile feedback was absent, delaying or removing visual feedback significantly affected the amount of time that participants spent looking at the in-vehicle system ($F(2,68) = 12.050$, $p < 0.001$), but tactile feedback reduced mean total glance time from 2.76s to 2.32s when visual feedback was delayed ($F(1,34) = 23.514$, $p < 0.001$), and from 2.96s to 2.40s when visual feedback was absent ($F(1,34) = 40.329$, $p < 0.001$). Tactile feedback improved ratings of enjoyment (like/dislike) by an average of 1.3 points ($p < 0.001$), confidence by an average of 2.1 points ($p < 0.001$), task difficulty by an average of 0.9 points ($p < 0.01$), and driving interference by an average of 0.8 points ($p < 0.01$).
Pitts, Skrypchuk, et al. (2012)	Menu navigation and button press tasks during a driving simulation performed on a touch screen in-vehicle system with audio, tactile, audio and tactile, or just visual feedback. N = 48.	Multimodal feedback had no effect on driving performance in the Lane Change Test, but users expressed a preference for multimodal feedback over visual feedback alone. Combined audio and tactile feedback was the most preferred. Combined visual-audio-tactile feedback significantly improved hedonic rating scores ($z = 4.29$, $p < 0.001$), confidence ratings ($z = 4.55$, $p < 0.005$), perceived task difficulty ($z = 2.76$, $p < 0.001$), and perceived driving interference ($z = 3.54$, $p < 0.001$) when compared with visual feedback only.
Pitts, Burnett, et al. (2012)	Search-and-select touch screen task during a driving simulation performed on a screen with either tactile feedback or visual feedback only. N = 36.	Tactile feedback improved task performance when visual feedback was delayed or removed and reduced the amount of time that participants spent looking at the in-vehicle system. Tactile feedback also elicited improved experience and usability ratings. Mean total glance time was reduced when tactile feedback was present. There was a statistically significant reduction in mean total glance time from 2.76 s to 2.32 s when visual feedback was delayed ($F(1,34) = 23.514$, $P < 0.001$) or nonexistent ($F(1,34) = 40.329$, $p < 0.001$). Mean primary glance time was reduced when tactile feedback was present. There was a statistically significant reduction in mean primary glance time from 2.48 s to 2.15 s when visual feedback was delayed ($F(1,34) = 23.824$, $p < 0.001$) or nonexistent ($F(1,34) = 15.893$, $p < 0.001$). Tactile feedback reduced primary glance count from 1.94 to 1.77 ($F(1,34) = 15.639$, $p < 0.001$).

About Immersion

Founded in 1993, Immersion is the leading innovator in haptic technology; the company's touch feedback solutions deliver a more compelling sense of the digital world. Using Immersion's high-fidelity haptic systems, partners can transform user experiences with unique and customizable touch feedback effects; excite the senses in games, videos and music; restore "mechanical" feel by providing intuitive and unmistakable confirmation; improve safety by overcoming distractions while driving or performing a medical procedure; and expand usability when audio and visual feedback are ineffective. Immersion's TouchSense technology provides haptics in mobile phone, automotive, gaming, medical and consumer electronics products from world-class companies. With over 1,300 issued or pending patents in the U.S. and other countries, Immersion helps bring the digital universe to life. Hear what we have to say at blog.immersion.com.

For additional information about tactile feedback, haptics, and the human response to specific haptic effects and performance parameters, contact Immersion at focus@immersion.com.

Many consumer studies and whitepapers are also available on Immersion web site. To access and download these documents, please visit http://www.immersion.com/whitepapers

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