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Haptic Interface for Vehicular Touch Screens

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Reducing Driver Distraction with Touchpad Physics

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ABSTRACT

Once the domain of purely physical controls such as knobs, levers, buttons, and sliders, the vehicle dash is rapidly transforming into a computer interface. This presents a challenge for drivers, because the physics-based cues which make traditional controls easy to operate with limited visual confirmation are absent on traditional screens. We investigate the addition of programmable physics-based cues to a visual display as a method to reduce eyes-off-road time. A TPaD variable friction touchpad was installed in the Ford VIRTTEX motion driving simulator. Subjects performed target acquisition and slider adjustment tasks under visual, visual/haptic, and haptic feedback conditions. For the two tasks, we found that the visual/haptic condition resulted in 39% and 19% decreases in total eyes-off-road time per task while showing negligible differences in task performance. Subjects showed a clear preference for combined visual and haptic feedback.

Author Keywords

Surface Haptics, Touchpad, Variable Friction

ACM Classification Keywords

H.5.2. Information interfaces and presentation (I.7): User Interfaces (D.2.2, H.1.2, I.3.6): Haptic I/O

General Terms

Human Factors; Design; Experimentation; Performance.

INTRODUCTION

For automobile interfaces, physical control objects such as knobs, levers, buttons, and sliders have served well, evolving with the car itself to suit the unique demands of a potentially stressful and distracting environment. However, the modern vehicle has transformed into a computer platform, and the amount of information that drivers can access and interact with within a vehicle has greatly increased in recent decades. There are navigation systems, entertainment systems, climate control systems, and vehicle performance systems, all of which demand display space and interaction elements. Traditional automobile-style controls having unique buttons for each function simply cannot keep pace. As they have for cell phones, designers are turning to touch based screen interfaces as the answer.

Screens by themselves are visual feedback devices, and interacting with them places a demand on the driver to look away from the road. In this research, we investigate the addition of force cues to the visual display as a possible method to reduce eyes-off-road time. A TPaD variable friction display was installed into the Ford VIRTTEX driving simulator as is shown in Figure 1.

The device operates similar to a laptop touchpad but with the addition of variable friction haptic feedback on the touch surface. Drivers were asked to complete two simple tasks under three different feedback conditions: visual only, visual plus haptic, and haptic feedback only.

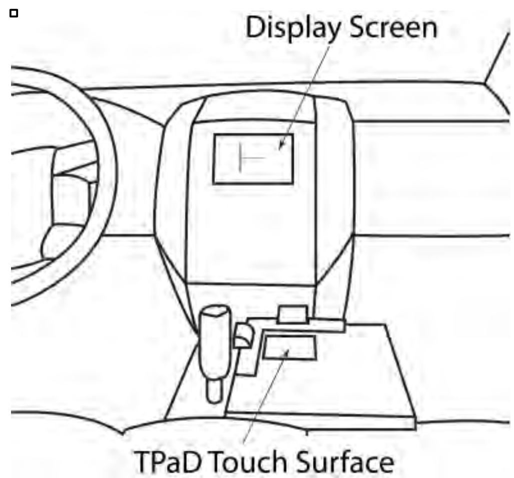

Figure 1- In vehicle setup of the touch surface and screen

The contributions of this research are as follows:

1. Measurement of total eyes-off-road time for the completion of tasks while driving, showing a significant reduction for tasks with haptic feedback.
2. Development of interaction techniques that allow simple tasks to be accomplished via haptic feedback with limited or no visual confirmation.
3. User survey data indicating a preference for tasks with both visual and haptic feedback, and indicating a positive response to the TPaD interface in general.

This paper begins with a review of screen interfaces in vehicles, driver distraction, and past research on adding physicality to screens through haptic feedback. The experimental setup and interface design are then described, followed by results, discussion and concluding remarks.

BACKGROUND

While their near ubiquity speaks to the success of touchscreens as a computer interface, their introduction into vehicles has received mixed reception. High spatial resolution and the fact that they can be changed on the fly means that much more information can be relayed in the same space, resulting in a much larger number of options for the interaction designer. At the same time, the driving environment is visually demanding, and these displays only add to visual demand. The traditional vehicle control elements have evolved over time to have physical properties like shape, texture, stiffness, and kinematic affordances that are conducive to purely haptic operation. For example, it is possible to feel for, acquire and operate a physical knob or slider without visual confirmation. However, the hard, flat surfaces of graphical interface objects offer no such tactile or kinesthetic feedback, and the user necessarily must rely on visual confirmation to complete any task [6]. Drivers resort to visual time sharing, pulling their eyes and attention away from the road.

Driver Distraction and Eyes-Off-Road Time

Driver eye glance behavior is a safety relevant measure, because it affects the driver's situational awareness. A driver's situational awareness can be reduced as glances away from the road scene ahead are longer, more frequent, or further away. For example, one driving simulator study found that the longest 22% of in-vehicle single glances away from the road scene were associated with 86% of collisions [13]. Based on a naturalistic driving study which videotaped 100 drivers over the course of a year, the US National Highway Traffic Safety Administration estimates that drivers taking their eyes off the forward roadway is a contributing factor to 60% of crashes, near crashes and incidents [16]. Specifically, they report that total glance times away from the road of 2.0 seconds or more within a 6 second interval increased crash risk by a factor of at least two relative to normal, baseline driving (i.e., randomly selected 6 second driving periods).

AUGMENTING SCREENS

Automakers have sought to decrease the visual demand of screens in a variety of ways. Strategies include duplicating touchscreen functionality with dedicated physical controls, bypassing the screen altogether with voice based interactions, and creating multipurpose physical interfaces with which to navigate the screens [12, 14]. For example, BMW offers a multifunction knob to navigate screens, and Lexus offers a type of force feedback joystick. While these adapted physical controllers do add haptic feedback that is otherwise lacking on screens, they separate the controller from the controller display, and are not reconfigurable to the degree that on-screen controls are.

One manufacturer, Cadillac, offers vibrotactile feedback on their in-dash touchscreen displays [12, 14]. This method begins to approach the promise of a reprogrammable physics display as it provides vibration feedback directly from the screen itself. However, the fact that it cannot control force limits the depth of the physical sense that it can convey. Vibrotactile feedback is but one of a new class of surface haptic feedback methods including electrovibration, shape-changing, skin stretch, friction control, and force control which are opening up the possibility of programmable physics [1, 7, 8, 15, 17, 21].

TPaD

In this research, we evaluate the in-vehicle use of a TPaD display in a touchpad configuration. The TPaD is capable of controlling the coefficient of friction, and consequently lateral resistance force between the surface and the user's fingertip. While touchpads have been researched as in-vehicle interfaces in the past [4, 5], and are even offered on certain Audi vehicles [12], the addition of the variable friction display allows physical force cues to be designed into the interaction.

Past studies have shown that variable friction haptic displays are able to increase performance for a simple targeting task [17]. It is not clear, however, that this performance advantage carries over to the driving environment. Task completion time decreases of fractions of a second are likely more significant for frequent interactions with a tablet or laptop compared to less-frequent interactions with displays within the vehicle. What becomes more important in a driving environment, however, is the amount of visual attention and consequently, the amount of eyes-off-road time that the task requires.

Research Questions

The research questions addressed in this paper stem from assessing the suitability of variable friction displays and by extension, programmable physics displays in general as in-vehicle control interfaces. Are users able to take advantage of physics-based cues in a complex driving environment which includes other forces and vibrations? Is surface haptic feedback alone enough to complete a task successfully, or must it be coupled with visual feedback? Does the additional feedback result in less eyes-off-road time? Will users prefer the haptic feedback, and will it make for a more satisfying experience?

EXPERIMENT

Equipment

TPaD Variable Friction Display

Different from past devices [17, 19], the TPaD (tactile pattern display) in this study was not set up in a touchscreen configuration. Rather, the display screen and the touch surface were decoupled as you would see for example in a laptop touchpad. The touch surface was placed below the center console, to the right of the floor shifter as is shown in

Figure 1. Past research has shown the resting position of the dominant hand to be the preferred location for a touchpad [4]. This allows the driver to rest his or her arm in a comfortable position throughout repeated experimental trials.

The touch surface was a square piece of glass with a usable surface area of 3" x 3". The construction of the TPaD surface, drive electronics, and the finger position sensing system is identical to the ActivePaD surface haptic device and its operation is fully explained in previous publication [19]. Because the surface of the TPaD is not completely uniform in its friction reduction, past targeting experiments have chosen to design tasks which only utilize uniform areas of the surface [17, 18]. For this study however, it was decided to treat the entire screen as if it were uniform which is considered to be a more realistic use case.

VIRTTEX

Ford's VIRtual Test Track EXperiment (VIRTTEX) is a motion-based driving simulator with force feedback and a surrounding visual environment. VIRTTEX is designed to accommodate a full-size, interchangeable vehicle cab, with a model year 2007 Ford Edge used as the test vehicle for this study. Tactile, visual, and sound cues are provided to the driver in order to fully immerse drivers into the driving task. Realistic road, wind, and engine sounds are played over a sound system [2]. The vehicle cab includes a steering control loader for accurate feedback of road and tire forces to the driver. The visual system in VIRTTEX is a front-projection display system onto a spherical display surface of radius 3.7 m. It covers full 360° viewing angles at 60 Hz refresh rate including an LCD monitor in the rear cab to provide the appropriate view for the rear-view mirror.

The vehicle buck rests on a motion platform that is hydraulically powered in 6 degrees of freedom (Figure 2) [10, 11]. The motion system has a bandwidth in excess of 13 Hz in all degrees of freedom. It is capable of up to .6 G of acceleration in the longitudinal and lateral directions over a displacement of +/- 1.6 m. It is meant to create a realistic, precisely controlled, and repeatable environment in which to conduct driving experiments.

Eye Tracking

A Seeing Machines faceLAB eye-tracking system was used to track the driver's gaze. Horizontal and vertical gaze coordinates generated by faceLAB in a world coordinate system were used to generate a Road/Not Road binary signal. This signal indicates whether the driver was looking to the exterior driving environment or somewhere in the vehicle interior. Extremely short looks away from the road (e.g., eye blinks) are removed by further processing the Road/Not Road signal according to SAE J2396 [24].

Figure 2- Exterior of VIRTTEX driving simulator

Study Protocol

Tasks

The tasks for this experiment were chosen to each represent a class of actions that are taken on screen interfaces. The first, the targeting task, represents general target acquisition tasks such as selecting a button. Ultimately, regardless of the control type displayed on the screen, the first step for the user is always to acquire it. The second task, the slider adjustment, represents any task requiring the selection of one choice among many. This includes a menu selection, a scroll wheel selection, or selection among an array of buttons.

Haptic Interface Design

The haptic representations of these two tasks were developed via iterative design process including interaction with pilot subjects, and guided by two main design principles. The first design principle was that the tasks should be achievable without visual feedback. That is, the haptic feedback should not only add to the affect of the experience, it should also clearly communicate enough information as to stand alone.

The second design principle was that the physics of the display should assist in completing the task. For example, a selection location should resist motion away from it, and a transition location should encourage motion through it. In this way, friction control is used as a way to afford movement. When friction is low, movement is afforded in both planar directions. When friction is high, no movement is afforded.

The fact that movement cannot be selectively afforded in one planar direction while restricted in the other had interesting consequences on the design of the tasks. For example, early prototypes of the slider adjustment task involved a circular knob that would slide in the horizontal direction. When the knob was acquired, friction was turned low in order to allow the finger to slide freely. However, since the finger was free to slide in the vertical direction as well, the user would often accidentally slide vertically off of the knob, causing confusion and invariably a look back to the screen to see what had happened. Since this violated the first design principle, the slider knob was changed to a vertical bar (Figure 3b), turning its acquisition into a one dimensional task.

Using the physics of the display to assist in task completion has been shown in at least one case to increase quantitative measures of task performance [17]. However, while testing prototypes, users would not always prefer physically assistive designs over alternatives. Given two choices of detent design, for example (low friction normally with high friction detents or high friction normally with low friction detents), there was no consensus on which was subjectively better. When probed further for the reasoning behind their preferences, users would describe different interpretations or mental models of what they saw and felt on the screen. Effort was taken therefore, to remove ambiguity where possible, and reinforce the correct mental model through visuals and through the description of the task.

Targeting Task

The target task is shown in Figure 3a. The target area is represented visually by a gray vertical bar, and the finger touch location is represented by a black vertical line. The target area is represented haptically by a high friction vertical bar of the same size as the visual while the rest of the screen is low friction. The task was to "acquire" the target by sliding the finger to within the target area. Subjects were instructed to place their finger down anywhere on the screen, slide all the way to the left until they hit the side of the screen, and then slide to the right and acquire the target, finally lifting their finger off the screen to indicate that they are done. The location of the target randomly varied between 45, 50, 55, or 60 mm from the starting line, which was defined as 8 mm from the left edge of the screen to account for the width of the finger. The width of the target area was 4 mm for all tasks.

Slider Adjustment Task

For the slider adjustment task, shown in Figures 3b and 3c, the gray vertical bar is the slider bar, and it can be slid to the left or right to any of the positions marked with a gray tick mark. The user acquires the slider bar by sliding over it, and the bar then follows the finger until it is lifted off the screen, at which point the bar snaps to the closest tick mark. A visual cue of a black dot represents the finger location until the bar is acquired. At that point, the dot disappears and the slider bar turns transparent (Figure 3c).

The haptic rendering initially is similar to the targeting task, a low friction screen with a high friction vertical bar (Figure 3b). Once the slider bar is acquired, low friction areas (detents) become active between the tick marks (Figure 3c). The low friction areas are separated by a center distance of 10.5 mm and are a width of 1.0 mm. The net result of this haptic design is that the finger slips and moves rapidly through the detent while resisting motion away from the tick mark. The task was to adjust the slider bar to the right by a randomly varied number of ticks between 2 and 4 as was requested in a voiceover.

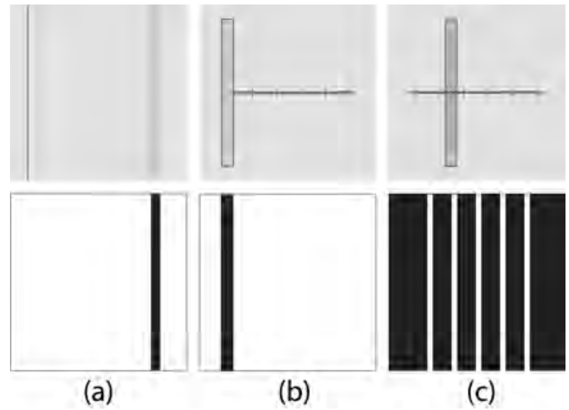

Figure 3 - The visual (top) and haptic (bottom) task displays. Black indicates high friction and white low friction. (a) Targeting task. (b) Slider task before bar acquisition. (c) Slider task after bar acquisition.

Driving Environment

The driving environment was designed to be controlled and repeatable, but also to have moderate attentional demands as a real-world driving environment would. In addition to the driver, an observer rode in the vehicle at all times, and a simulator operator in the control room was available via intercom. Figure 4 shows a driver within the simulator during a drive. The environment was a four lane urban road with 3.2 m lane widths and moderate traffic both oncoming and passing to the left. There were stoplights, but they were always green. The driver was instructed to stay in the right lane for the entire drive, neither passing nor merging.

Figure 4- Driver in VIRTTEX driving simulator

Drivers were also instructed to follow a lead vehicle (Figure 5) within a safe following distance, defined as 2-4 second headway at 40 mph or 36-74 m. During the drive, the next task would not begin if the vehicle exceeded this bound or was out of a 35-45 mph speed range. In these cases, the driver was given 10 seconds to return to a safe following distance. If they remained outside the bounds longer, the simulator operator would instruct them to either catch up to or fall back from the lead vehicle.

While the aforementioned steps of removing the common attentional demands of lane changing and stopping were taken to create uniformity across the drive, a reasonable amount of demand was desired. To that end, a detection task involving an "erratic vehicle" was added. The erratic vehicle drove ahead of the lead vehicle, and at random intervals would swerve over half way (1.6 m) into the lane to the left (Figure 5) or half way onto the shoulder to the right. Each partial lane deviation lasted for 3 seconds: one second for the vehicle to deviate half a lane width, one second at the half-lane-width deviation, and one second to move back into its lane. The subject was instructed to watch for this, and announce whenever they spotted the erratic driver by saying "left" or "right" respectively.

Figure 5- The driving environment showing the lead vehicle (white van) and erratic vehicle (blue car).

Participants

Twenty five volunteers were recruited from an email sent to over 1000 Ford employees over an internal listserv. Respondents were directed to a website to fill out demographic and screening information. Right handed subjects [24/25] were preferentially recruited because the touchpad was setup in position for the right hand. Subjects without eyeglasses were also preferentially recruited [21/25] due to limitations of the eye tracking equipment. The subjects were balanced across age [13 18-40; 12 40+] and gender [12 male]. Subjects were asked how often they drive with 23 responding "almost daily" and 2 responding "at least weekly." Subjects were also asked how often they interact with a touch-screen device. 18 responded "almost daily", 2 "at least weekly," 2 "at least monthly," and 3 responded "not at all." This study was approved by the Institutional Review Board of Northwestern University, and all subjects gave informed consent.

Pre-Drive Training

In order to ensure consistency of instruction between subjects, a script was followed. The training began with a VIRTTEX safety video. This was followed by a short introduction to the drive which emphasized that their primary task was to drive safely, including detecting the erratic vehicle. The touchpad tasks were introduced as secondary tasks that they should "do their best" to complete while still driving safely.

Participants were allowed to interact with the tasks before the drive. They were first told to "explore the task" and figure out how it worked on their own, and then specific instructions of how to complete each task were given. Subjects practiced each of the two tasks with each of the three feedback conditions. They completed each a minimum of 5 times and were allowed to continue practicing until they responded that they were confident that they could complete the task.

Surface moisture is known to have a significant effect on the coefficient of friction of the fingertip [22, 23]. In order to reduce the variability of the effect, each subject was asked to rub their first two fingers of their right hand in magnesium carbonate (climber's chalk) and then wipe off the excess dust. In order to prepare the surface uniformly for each subject, the glass surface was wiped with a dry paper towel. While fingertip pressure is known to affect friction as well [9], no attempt was made to control it. Rather, in training, subjects were instructed to try applying different amounts of pressure with either of their fingers in order to find a level that felt good to them. During the drive, they were left free to switch fingers as they saw fit.

For many participants, the TPaD generates a high frequency noise when it is on and in contact with the finger. In order to mask this, pink noise was added to the simulator audio and played on over-the-ear headphones during the entire experiment. The level of noise was set in training by having the subject interact with the device while listening for the device noise, gradually increasing the pink noise until the subject indicated that they could no longer hear the device.

Drive

The driving portion of the study began with 2 practice trials for each task and feedback case combination. The main study began with the targeting tasks and concluded with the slider tasks. The study was designed to be entirely within subject with every subject completing the same number of the same tasks. The task trials were administered in 6 blocks of 5 for the targeting task and 6 blocks of 4 for the slider task for a total of 54 task repetitions. Each block contained a single feedback case of visual only, visual plus haptic, or haptic only. The order of the blocks was generated pseudo-randomly with the same feedback case not allowed to repeat twice in a row.

Each block was introduced by a recorded, computer generated voiceover announcing "Do targeting (or slider) task until further notice" followed by a second voiceover announcing "Touch feedback on (or off)." For the slider adjustment tasks, an additional voiceover indicating the target, "Increase by 3 (or 2, 4)" was played before each task. A ding indicated when to begin each task, and after completing each task, the subject was instructed to say "done" aloud. These two events marked the beginning and end of the task interval. The experiment took one and a half hours in total with the drive portion lasting approximately twenty minutes.

RESULTS

Eye Glance Behavior

Eye glances away from the forward roadway were analyzed for each driver. Specifically, the durations of individual eye glances away from the road during each task were calculated by analyzing the eye-tracking signal described earlier. The total eyes-off-road time (EORT) for a task is defined as the sum of the individual glance durations within the task interval. Eye glances initiating before the start of the task interval but continuing into it as well as glances initiating during the task interval and continuing past its end are included in the sum.

Total EORT per task was computed for all tasks and is plotted in Figure 6 as a function of both task type and visual/haptic feedback. Table 1 contains quartile values. All outliers were confirmed for accuracy with video review. Initial review of the data revealed that the distribution of data points had major clusters at zero glance duration. Because of this, non-parametric analysis was used. For the targeting task, the key results show a 0.67 second decrease in median total EORT per task (39%) between the visual (V) and the visual plus haptic (VH) cases.

A Mann-Whitney test confirmed that this result was significant (U = 43046, p = <.0001, r = .54). For the slider task, between V and VH, there is a corresponding decrease of 0.41 seconds (19%) in median total EORT per task. (U = 13405, p = 6.6E-4, r = .218). Additionally, 24% of the VH targeting tasks were completed without a single glance away from the road, as well as 10% of the VH slider tasks. No V tasks were completed without a glance away from the road. As is to be expected, the haptic only (H) cases resulted in significantly less EORT than either V or VH for both tasks.

Total Glance Duration (sec)	Lower Quartile	Median	Upper Quartile
Targeting V	1.36	1.72	2.24
Targeting VH	0.21	1.05	1.79
Targeting H	0.0	0.0	0.57
Slider V	1.42	2.19	2.79
Slider VH	0.92	1.78	2.59
Slider H	0.0	0.26	0.70

Table 1- Total Eyes-Off-Road Time Per Task Values

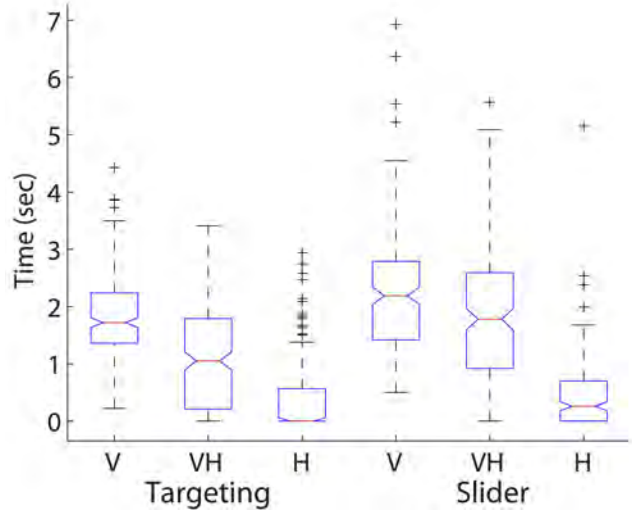

Figure 6 – Total Eyes-Off-Road Time Per Task

Task Performance

Each task was evaluated as successfully completed or not. For the target task, success was defined as the last finger position before liftoff being within the bounds of the target bar. The results are plotted in Figure 7. The V and VH cases of the target task had a success ratio of 92.4% and 89.1% respectively with a 20% drop to 69.1% for the H case. For the slider task, success was defined as a match between the position of the slider at the end of the response interval and the position which was instructed. The slider task had a success ratio of 96.4% and 95.8% for the visual and visual plus haptic cases with a 45.8% drop to 50.0% for the haptic only case.

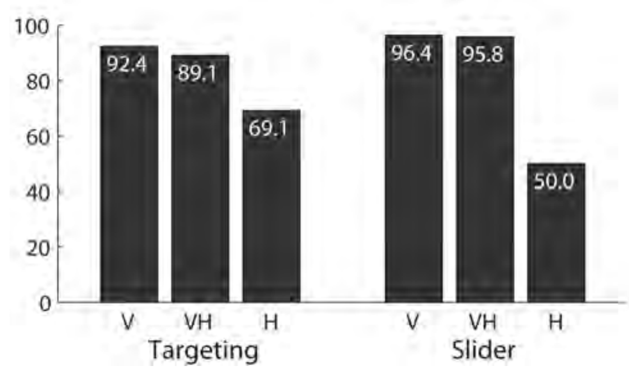

Figure 7 – Task Percentage Correct

USER EVALUATION

After the drive was completed, each participant was asked to complete a series of questionnaires.

Task Load Comparison

In order to assess the participants' perception of demand, each was given a task load comparison questionnaire derived from the NASA Task Load Index [20]. Each question is intended to measure a separate dimension of

workload. This compared the targeting and slider tasks, each as a function of the three feedback conditions. Each question was presented with three 5 point scales, one for each feedback condition. The scales were labeled 1-5, with descriptors "Very Low" and "Very High" at 1 and 5 respectively. The questions were as follows:

TL1. How mentally demanding were the tasks?
TL2. How visually demanding were the tasks?
TL3. How successful were you in accomplishing what you were asked to do?
TL4. How hard did you have to work to accomplish your level of performance?
TL5. How insecure, discouraged, irritated, stressed and annoyed were you?

System Usability Survey

Selected questions were taken from the SUS system usability scale [3]. Subjects were instructed to consider the system as the haptic feedback system, and to think of the tasks that contained both visual and haptic feedback. Each statement was rated on a 5 point scale from greatly disagree (1) to greatly agree (5):

SU1. I think that I would like to use this system frequently.
SU2. I thought there was too much inconsistency in this system.
SU3. I would imagine that most people would learn to use this system very quickly.
SU4. I found the system very cumbersome to use.
SU5. I felt very confident using the system.
SU6. I would turn this system off if it were in my car.

Haptic Feedback Evaluation

The haptic feedback evaluation was meant to capture subjective impressions of the system as a whole and not particular tasks. Each question was rated on a 5 point scale from greatly disagree (1) to greatly agree (5). While you were driving, did you notice the tactile feedback? If so, would you agree that the tactile feedback was…

HF1. Weak?
HF2. Preferred?
HF3. Annoying?
HF4. Matched the visuals?
HF5. Helpful?

Free Response-

Finally, in order to capture greater depth of understanding, the final questionnaire was open-ended typed free response.

FR1. What was your impression when you felt the haptic feedback for the first time?
FR2. How did you complete the target acquisition task in the different cases? (visual only, haptic plus visual, haptic only)
FR3. How did you complete the slider task in the different cases? (visual only, haptic plus visual, haptic only)
FR4. What did you like about the haptic feedback?
FR5. What didn't you like about the haptic feedback?
FR6. Free response. Please expand on any previous questions, and add comments.

User Evaluation Results

The distribution of responses for the task load comparison questionnaire (TL1-TL5) of V, VH and H are plotted in Figures 8 and 9. The red vertical lines and corresponding values indicate the means.

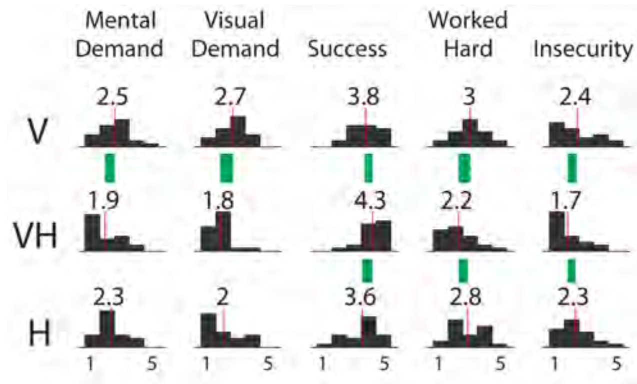

Figure 8- Task load responses for target task. Red lines and values indicate means, and green bars indicate significance between the corresponding pairs.

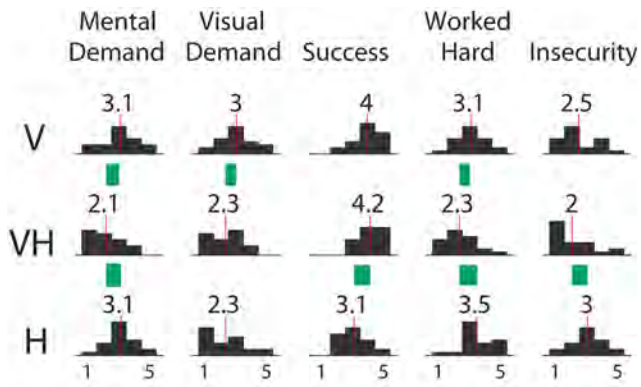

Figure 9- Task load responses for slider task. Red lines and values indicate means, and green bars indicate significance between the corresponding pairs.

Visual vs. Visual Plus Haptic

Pairwise comparisons were done on the results of the task load assessment between the V and VH cases. For the targeting task, the VH case was rated significantly more favorably than the V case in every workload dimension. Significance levels from Wilcoxon signed rank tests are shown in Table 2 with significant results highlighted blue. Subjects found the VH condition to be the least mentally demanding with 12 of 23 participants responding "very low." Despite showing identical visual displays, the VH case was reported as less visually demanding than the V case with 21 of 23 responding "low" or "very low" for the target task. For the slider adjustment task, VH was rated as requiring significantly less mental and visual demand, as well as requiring the user to work less hard than in the V case. Significant results are also in Table 2 as well as being noted with a green connecting bar in Figures 8 and 9. For example, in Figure 8, the distribution plots of V and VH for mental demand are connected by a green bar and are thus indicated significant, while the plots of VH and H for mental demand are not.

TL1. Tar. Mental Demand	W(18) = 36.0	p = .027
TL2. Tar. Visual Demand	W(16) = 16.0	p = .006
TL3. Tar. Success	W(16) = 30.0	p = .041
TL4. Tar. How Hard Work	W(18) = 30.5	p = .014
TL5. Tar. How Insecure	W(11) = 7.5	p = .020
TL1. Slider Mental Demand	W(17) = 6.0	p = .0005
TL2. Slider Visual Demand	W(17) = 21.0	p = .006
TL3. Slider Success	W(13) = 30.5	p = .364
TL4. Slider How Hard Work	W(18) = 36.5	p = .027
TL5. Slider How Insecure	W(12) = 16.5	p = .078

Table 2- Significance levels comparing visual to visual plus haptic for task load questionnaire

Haptic vs. Visual Plus Haptic

Pairwise comparisons were also done on the results of the task load assessment between the H and VH cases. For the slider task, the VH case was rated as significantly less mentally demanding than the H case (W(18) = 6.0, p = .0005). Subjects rated the VH case was as being significantly more successful for both the targeting (W(15) = 18.0, p = .0144) and the slider (W(18) = 17.0, p = .0021) tasks. Subjects also rated the VH case as requiring them to work less hard than the H case for both the targeting (W(15) = 22.0, p = .0269) and the slider (W(17) = 14.5, p = .0029) tasks. Finally, the VH case was rated as causing significantly less insecurity and discouragement for both the targeting and slider tasks (W(12) = 5.5, p = .0054; W(15) = 4.5, p = .0005).

The general trend in these responses is for VH to be rated most favorably. For every question, including those found to be not significant, the mean response value indicates a favorable (or tied) mean task load rating for the VH case compared to either the V case or the H case.

Subjects reported high success for all cases of both tasks, with greater success for the VH case and less success for the H case. This result is slightly at odds with the actual success rate, indicating that the addition of haptic feedback to the visual case increased the users' *perception* of success without increasing the actual success rate.

The results of the system usability survey are shown in Figure 10, and the haptic feedback evaluation in Figure 11. The mean responses of both the haptic feedback evaluation and the system usability survey all favored haptic feedback.

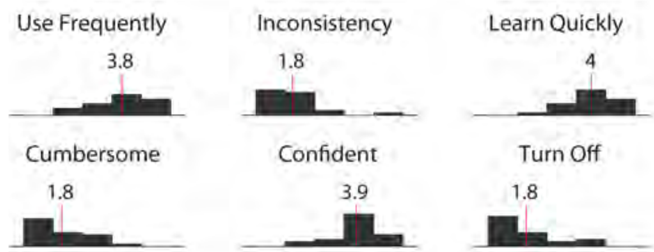

Figure 10- System usability survey responses. 1 = greatly disagree, 5 = greatly agree (SU1-SU6)

Figure 11- Haptic feedback evaluation. 1 = greatly disagree, 5 = greatly agree. (HF1-HF5)

DISCUSSION

Significance of Eyes-Off-Road Time

The primary finding of this paper is that by adding haptic feedback to an otherwise visual task on a touchpad, drivers spend significantly less time looking away from the road. Many subjects described a strategy where they attempted to complete the task as best they could without looking away from the road, then taking a quick glance to the screen to confirm their selection. Said one participant, "For the visual, I looked at the screen the entire time. For the combined haptic and visual I completed the task without looking and then looked briefly to make sure I was in the bar." This is a significant positive change in behavior, as longer glances (those over 2.0 seconds) have been observed to result in increased risk of crash or near-crash involvement [16].

Performing Tasks Without Visual Feedback

Though the success ratio decreased for the haptic only cases, users were able to perform the tasks without any visual feedback. Though the success ratio for haptic only was better than random chance, these success rates for these tasks in particular are likely too low for use in a driving environment. Subjects performed much better (Figure 7) and also perceived their performance as improved (Figures 8, 9) when given both of the two feedback modes and allowed to choose. This is supported by the fact that 24% of the targeting tasks and 10% of the slider tasks were performed without a single glance away from the road in the VH case. Said one user about the visual plus haptic target task, "At first I looked toward the screen, after a couple of times though, I didn't need to look any longer." This anecdote was confirmed in the data.

It is also interesting to see that though there was nothing for the drivers to see by looking at the screen, there were nonetheless many eyes-off-road glances for the haptic only feedback cases. One user's comments may provide insight into this, "For the haptic only, I looked involuntarily the first couple times and then seemed to get used to doing it without looking." While this study focused on a vehicle environment, the car is only one example of an environment with limited sight or split attention. The device may be suitable for other visually demanding environments.

Subjective Response

The most interesting result from the subjective data is a clear preference for the addition of haptic feedback to the visual display. The numerical responses are supported by the comments:

"Haptic plus visual was the most helpful one, followed by haptic only because then I did not have to take my eyes off the road. Visual only was the most difficult one because I had to dedicate my whole attention to the screen."

"It was a good addition to the visual feedback and once you get used to it allowed you to place more focus on the driving."

"…[T]he combination was the best use because I could leave my eyes on the road and was relying on multiple senses."

"Visual was fine but haptic plus visual was clearly the best."

As is supported by the numerical responses to the system usability and haptic feedback evaluation surveys, the written free responses indicate that most users had a positive opinion of the TPaD system overall. In response to the question, "What didn't you like about the haptic feedback?" two users expressed that the feedback was weak and difficult to feel, while one user reported a numb feeling in both of the fingers they used on the screen. In response to the question, "What did you like about the haptic feedback?" nine users expressed that they liked being able to keep their eyes on the road, while seven users independently ventured that they liked the way that it felt.

To our knowledge, this experiment was the first instance of testing a variable friction display within a vibrating and accelerating environment. Though a direct comparison between a moving driving simulator and a motionless environment was not made, the motion seemed not to interfere with the operation or the sense of the haptic feedback. From the results of the total EORT measurements and the lack of any user comments to the contrary, it is inferred that the haptic effects could be distinguished during motion.

Design Recommendations

Informal observation suggests that the subjects continued to become more comfortable and capable with the TPaD as the drive went on. Said one subject of their first impression, "interesting, never really used it before, easy to figure out, didn't take long to figure. after 5 minutes, could do it quick." This suggests a progression of learning that may not only increase the performance of these relatively simple tasks over time, but may also allow the progression to more complicated, multi-step tasks. Because the variable friction display is so novel, it is recommended that new users are allowed to ease into the feeling, first just experiencing it, then moving to simple tasks, and then to tasks that require finer distinction, higher spatial resolution, more complex physics, and multiple steps.

Because users voiced a strong preference for visual plus haptic over haptic alone, it is recommended that visual cues accompany haptic feedback for most applications. However, despite the measured decrease in success rate for these tasks, haptic only tasks should not be abandoned for future interface designs. Said one subject, "Visual and haptics together really easy, surprised at how easy just haptics were still." There are many variables which may improve the success rate of haptic only interactions including increased effect strength, improved device design, different types of tasks, or simply better task design. These tasks used only the modulation of friction in a binary type "full on/ full off" mode. It is likely possible to improve the performance and increase the task complexity without visuals through the use of friction gradients and textures, and with surface haptic devices capable of active forcing [8, 19].

Although not investigated in this study, audio feedback is also an interesting addition to any virtual control object, and could work well together with haptic feedback. For example, while adjustment of a virtual volume slider would be completed with audio feedback, the user could benefit from haptics by being able to acquire the slider through feeling. One might imagine that with each additional sensory mode, the realism of virtual objects will increase.

While it is shown here that the addition of programmable physics to a touchpad display *can* improve performance and user preference, it is not necessarily always so. For early prototypes, it was not uncommon that users would respond that they preferred the haptic feedback off, or that they would be unable to complete the task without visual feedback. If the physical cues are ambiguous or otherwise confusing, they are as likely to hurt as to help. As with any other interface, thoughtful design is critical to successful implementation.

CONCLUSION

We found that adding haptic feedback to the visual display resulted in a 39% decrease in total eyes-off-road time per task for the target acquisition task and a 19% decrease for the slider adjustment task. We also found that subjects were able to complete the tasks with only the haptic display, but with a 20% and 45.8% reduction in success for the target and slider tasks respectively. Subjective responses were favorable for the system as a whole, and also showed a preference for the visual plus haptic feedback condition.

To our knowledge, this was the first deployment of a programmable friction display in a driving environment. While improved user experience and preference perhaps are able to stand alone as strong reasons for continued development and deployment of programmable friction displays, the results of this study show that tasks can be designed to improve measures of driver attention as well.

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WORKS CITED

1. Bau, O., Poupyrev, I. Israr, A., Harrison, C. Teslatouch: electro-vibration for touch surfaces. *Proc. UIST 2010* ACM Press (2010) 283-292.
2. Blommer, M., Greenberg, J., Realistic 3D Sound Simulation in the VIRTTEX Driving Simulator. *Proc. of DSC North America*, Dearborn, MI. (2003).
3. Brooke, J. SUS- A quick and dirty usability scale, Digital Equipment Corporation. http://hell.meiert.org/core/pdf/sus.pdf
4. Burnett, G.E., Lawson, G., Millen, L., Pickering, C., Webber, E. Designing touchpad user-interfaces for right-hand drive vehicles: an investigation into where the touchpad should be located. *Behav.& Inf. Technol. (*2012).
5. Burnett, G.E., Lawson, G., Millen, L. Pickering, C. Designing touchpad user-interfaces for vehicles: which tasks are most suitable?. *Behav. Inf. Technol.* 30, 3 (2011), 403-414.
6. Burnett, G. E., Porter, J.M. Ubiquitous Computing Cars: Designing Controls for Non-visual Use. *Int. J. Human-Computer Studies* 55 (2001), 521-531.
7. Casiez, G., Roussel, N., Vanbelleghem, R., Giraud, F. Surfpad: riding towards targets on a squeeze film effect. CHI (2011): 2491-2500
8. Dai, X., Colgate, J.E., Peshkin, M.A., 2012. LateralPaD: A Surface-Haptic Device That Produces Lateral Forces on A Bare Finger. *Haptics Symposium 2012,* IEEE (2012), 7-14.
9. Derler, S., Gerhardt, L.-C., Lenz, A., Bertaux, E., Hadad, M. Friction of human skin against smooth and rough glass as a function of the contact pressure. *Tribology International* (2008).
10. Grant, P., Artz, B., Greenberg, J., and Cathey, L. Motion Characteristics of the VIRTTEX Motion System. *Conf. Proceedings, HCTSC* (2001).
11. Greenberg, J., Artz, B., and Cathey, L. The Effect of Lateral Motion Cues During Simulated Driving. *Proceedings of DSC North America* (2003).
12. Grobart, Sam. Touch, Speak, Tap: Taking 5 Connected Cars for a Spin. *NY Times* (June 8, 2012).
13. Horrey, W., and Wickens, C. In-vehicle glance durations: Distributions, tails, and a model of crash risk. Trans. Research Record (2007), 22-28.
14. Immersion Corporation http://www.immersion.com/haptics-technology/haptics-in-use/automotive.html
15. Iwata, H., Yano, H., Nakaizumi, F., Kawamura, R. Project feelex: adding haptic surfact to graphics. *Proc. UIST 2002* ACM (2002) 51-60.
16. Klauer, S.G., Dingus, T.A., Neale, V.L., Sudweeks, J., Ramsey. The Impact of Driver Inattention on Near-Crash/Crash Risk: An Analysis Using the 100-Car Naturalistic Driving Study Data. National Highway Traffic Safety Administration (2006).
17. Lévesque, V., Oram, L., MacLean, K., Cockburn, A., Marchuk, N., Johnson, D., Colgate, J.E., Peshkin, M.A. Enhancing physicality in touch interaction with programmable friction. *Proc. CHI '11.* ACM Press (2011), 2481-2490.
18. Marchuk, N., Colgate, J.E., Peshkin, M.A. Friction measurements on a large area TPaD. *Haptics Symposium 2010*. IEEE (2010), 303-305.
19. Mullenbach, J., Johnson, D., Colgate, J.E., Peshkin, M.A. ActivePaD Surface Haptic Device. *Proc. Haptics Symposium 2012*, IEEE (407-414).
20. NASA. Nasa Task Load Index (TLX) v. 1.0 Manual (1986).
21. Pasquero, J., Hayward, V. Tactile feedback can assist vision during mobile interactions. *Proc. CHI '11* ACM Press (2011) 3277-3280.
22. Pasumarty, S., Johnson, S., Watson, S., Adams, M. Friction of the human finger pad: influence of moisture, occlusion and velocity. *Tribol. Lett.* 44, (2011), 117-137
23. Tomlinson, S.E., Lewis, R., Liu, X., Texier, C., Carre, M.J. Understanding the friction mechanisms between the human finger and flat contacting surfaces in moist conditions. *Tribol. Lett.* 41, (2011), 283-294
24. Society of Automotive Engineering. *Definitions and Experimental Measures Related to the Specification of Driver Visual Behavior Using Video Based Techniques.* Surface Vehicle Recommended Practice J2396, (2000).