A Pneumatic Tactile Alerting System for the Driving Environment

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ABSTRACT

Sensory overloaded environments present an opportunity for innovative design in the area of Human-Machine Interaction. In this paper we study the usefulness of a tactile display in the automobile environment. Our approach uses a simple pneumatic pump to produce pulsations of varying frequencies on the driver's hands through a car steering wheel fitted with inflatable pads. The goal of the project is to evaluate the effectiveness of such a system in alerting the driver of a possible problem, when it is used to augment the visual display presently used in automobiles. A steering wheel that provides haptic feedback using pneumatic pockets was developed to test our hypothesis. The steering wheel can pulsate at different frequencies. The system was tested in a simple multitasking paradigm on several subjects and their reaction times to different stimuli were measured and analyzed. For these experiments, we found that using a tactile feedback device lowers reaction time significantly and that modulating frequency of vibration provides extra information that can reduce the time necessary to identify a problem.

1 INTRODUCTION

The sensory overloaded driving environment.

Driving a vehicle can be a stressful experience. Other vehicles, changing speed limits, cyclists and pedestrians can overwhelm the vision sense. Horns, air-hammers, conversation, children in the back seat and the radio can overwhelm the auditory sense. Cockpit warning systems used in vehicles today additionally rely on those two senses to attract the driver's attention to important information, making driving a vehicle a sensory overloaded task.

Using haptic displays in vehicles

There have been studies regarding safety and performance in perceptually overloaded tasks such as driving [1, 2]. Most of these studies have concentrated on the auditory tasks in the driving environment. Several other studies have been made regarding the conveying of information through vibratory tactile means [4,5,6].

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In this paper we will investigate a novel way to attract the attention of a driver who may already be fully utilizing his vision and auditory attention. Mental workload is the ratio of demand to allocated resources [8]. Studies in psychology recommend combining input modalities as a means of balancing mental workload [4]. Haptic displays have several strengths: They can attract the attention of the user by actively stimulating the tactile sense, a mechanism not commonly used in the driving environment. They can convey meaning and produce stimuli at several locations in the driver's environment (steering wheel, motorcycle handlebars, aircraft control yoke, seat, gear shift, pedals etc.)

There are many applications for this type of display in the driving environment. A vibratory haptic display could be used in automobiles, aircraft or motorcycles. Engine problems, low fuel level, proximity to the car in front or back (especially useful in parking), and motorcycle turn signals left on are examples of information that might be displayed on this type of display.

By varying content of haptic signal (location, waveform, duration, intensity, amplitude, frequency) the haptic display can aid the user in quickly identifying the message being conveyed. This could be especially useful in aircraft cockpits where there are several dozen gauges and instruments, especially at times of high pilot workload such as approach or landing; however, the cognitive effort in processing these signals during stressful moments must be evaluated experimentally.

This new way of presenting feedback to a vehicle operator could radically change the way dashboards, cockpits and control panels are designed.

2 APPROACH

Evaluating haptic feedback on a steering wheel.

The objective of the work described here was to evaluate the effectiveness of a haptic device that could be used in a driving environment. We decided to look specifically at adding haptic feedback to a steering wheel to inform the user of a problem. Our hypothesis was that a haptic device would alert the user to a possible problem and could be used to aid the user in identifying the problem.

A "mock" steering wheel was constructed to simulate that of an automobile (Fig. 1). This steering wheel was fitted with a pneumatic pocket and a specially constructed computer controlled pneumatic pump. The pump could rapidly inflate and deflate the pneumatic pocket creating a pulsating sensation in the steering wheel that could easily be felt by the user when his/her hand was placed on the pocket.

One of the many advantages of using "touch" for relaying information is its inherent ability to allow fast reflexive motor responses to haptic stimuli [3], thus one can get a quick reaction from the user when stimulated by a haptic signal.

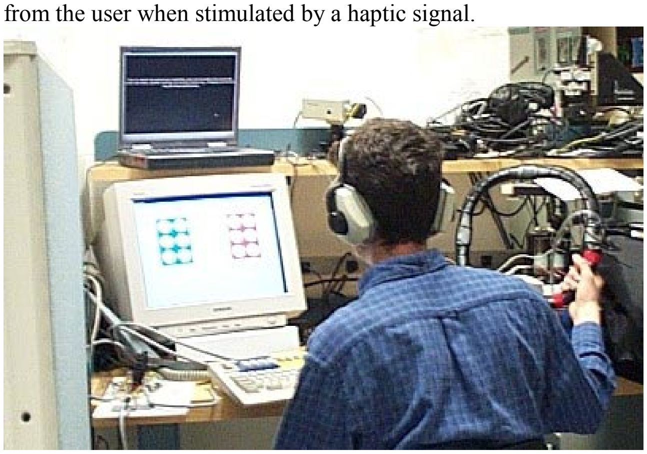

Figure 1. Test setup

To evaluate the device's effectiveness, two experiments were designed to measure the time required to recognize and identify a possible problem. In order to make the tests suggestive of a driving environment, a situation was constructed where the subject had to concentrate on other tasks, similar to a driver looking out the windshield of an automobile [7]. These two experiments evaluated (a) whether the haptic device increased the incidence and speed with which a "driver" noticed a possible problem, and (b) whether the device could reduce the time required to successfully *identify* the problem once an exception was noticed.

Each of the experiments was conducted on a number of users to quantitatively evaluate the performance improvement using the device. The primary measurement was the amount of time the user required to successfully recognize and identify a problem. The number of times the user did not ever successfully recognize or identify a problem was also recorded and analyzed.

Due to time constraints and available resources; these experiments are limited in that this setup does not capture all of the relevant aspects of an actual driving environment (e.g. multiple distracting tasks, longer duration, and higher consequences of errors). However, we feel they make an important first approximation in evaluating a novel display's effectiveness.

3 SETUP

3.1 Pneumatic Display

A pneumatic feedback device was chosen to provide the vibratory stimulus on the steering wheel. Pneumatic feedback has the following benefits:

- By using a pneumatic pocket, the vibratory stimulus could be localized to a specific area. Instead of shaking the entire steering wheel, the pneumatic pocket only provides a stimulus where it is located. This allows multiple stimuli to be provided on the steering wheel, and minimizes extraneous disruptions. (Conversely, you have to touch that part of the wheel.)
- The pump mechanism could be mounted remotely from the steering wheel, minimizing changes to the existing steering wheel. Signals or messages could be passed to the steering wheel through narrow flexible tubing.
- Changing the shape or configuration of the pneumatic pocket could change the "feel" of the stimulus relatively easily.

Using pneumatics also presented us with the following problems:

- Control of leaks
- Air compressibility limits both the force that can be generated and the distance between the pump and the pneumatic pocket.
- The range of salient frequencies is limited.

The design of the pneumatic pocket underwent several iterations. Figure 2 shows a number of the materials and configurations employed. These include rubber balloons, a small bicycle inner tube, and finally electrical shrink tubing.

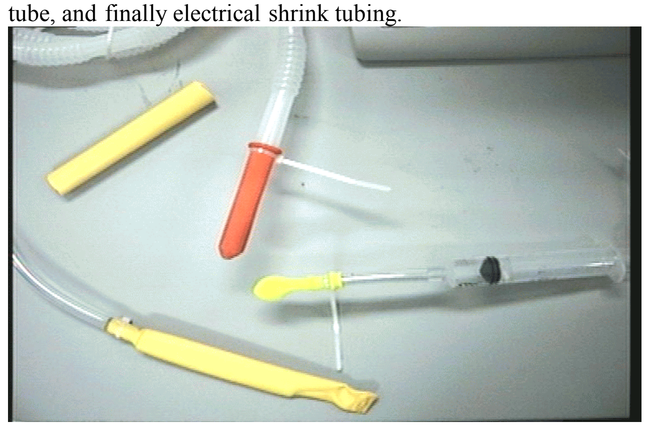

Figure 2. Pneumatic displays.

Shrink tubing is a thin-walled flexible plastic tube that is normally used for protecting electrical connections. Several diameters and brands of shrink tubing were tried until a 10 cm. long, 1cm. diameter tube was found to give the most salient sensation when mounted on the steering wheel.

3.2 Pump Mechanism

Initially, the pneumatic pockets were inflated and deflated using a small medical syringe. Although this was effective when inflating the pockets manually, the syringe required a large force to overcome friction. The syringe was replaced with a small AirPot™ actuator. The AirPot™ actuator (Fig. 3) is composed of a graphite piston inside a glass cylinder that is capable of producing high pneumatic pressures with very little friction.

3.2.1 Prototype 1

To keep the design simple and effective, the pump was constructed with a crankshaft style connection between the DC motor and the actuator. The first prototype was built with an AirPot™ actuator, a Maxon™ DC motor, and a number of Lego™ blocks and gears.

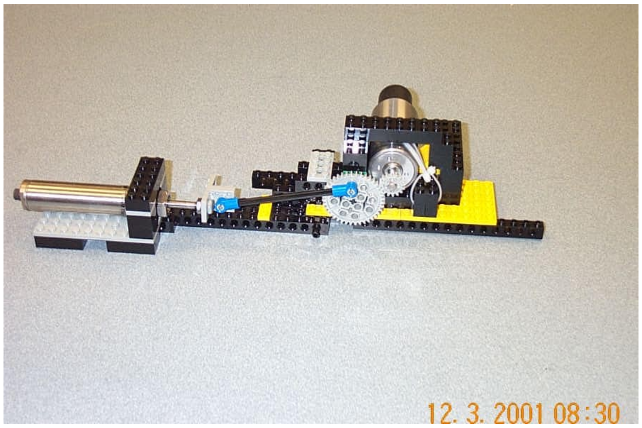

Figure 3. Pump prototype 1.
The motor & gearing on the right, drives an AirPot™ piston (left) in reciprocating motion. The AirPot™ actuator would normally be connected to a pneumatic tube output.

The crankshaft style design was chosen because of its simplicity and because using less than the full travel of the actuator (for varying amplitude) produced too soft a response on our haptic display. This constrained our design to a single amplitude of piston motion.

The first prototype allowed us to demonstrate our concept and test the pneumatic display, but the lack of structural stability caused the motor and actuator to vibrate excessively at high frequencies. The next prototype was constructed using the same design but with a structurally stronger base so that the range of frequencies could be increased.

3.2.2 Prototype 2

Prototype 2 was built similar to prototype 1, but with a more stable and strong wood platform. This reduced the vibration of the mechanism and allowed for higher frequencies. We were able to generate a maximum frequency of 10 Hz., again limited by prototype gearing.

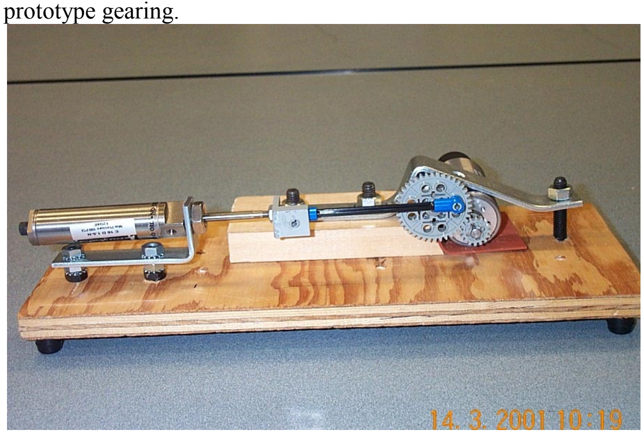

Figure 4. Prototype 2

The second pump prototype was sufficiently strong for the rest of the testing. This second prototype generated some audible noise, particularly at high frequency. To ensure that subjects received only haptic stimuli and no audio stimuli, the prototype was housed inside a cardboard box and wrapped in sound insulating material during experiments.

3.3 Steering Wheel

The steering wheel was constructed from PVC electrical conduit covered with a vinyl steering wheel cover. The inflatable actuator was mounted beneath the cover. This realistically simulated the feel of an actual steering wheel and was able to produce the required haptic stimuli.

Although the present steering wheel only contained one haptic display, future models could accommodate eight or more such devices. This could broaden the palette of sensations possible to be generated.

Figure 5. Haptic steering wheel. Built from PVC conduit and a vinyl steering wheel cover; the pneumatic display is located beneath the steering wheel cover, under the subject's right hand.

3.4 Software

In order to recreate the single driving environment attribute we felt most critical (multitasking), we created two pieces of software, a Graphical Dashboard simulation and a Primary Driving Task program.

3.4.1 Primary Driving Task Program

The primary driving program was meant to simulate the task of a driver concentrating on the outside environment. To accomplish this, a separate computer screen was placed above the Graphical Dashboard Simulator program (fig.7) to display sentences (Fig.6) that the subject was expected to read aloud.

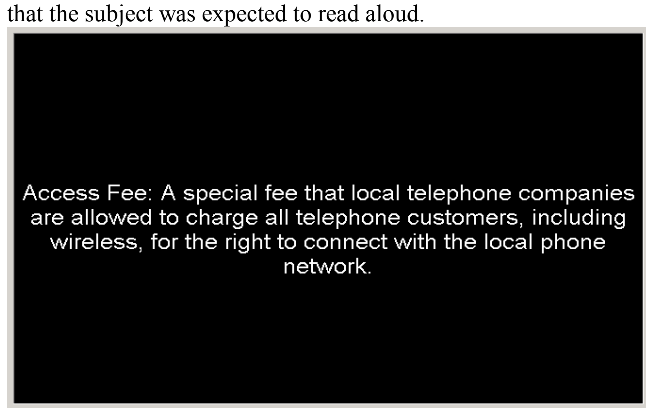

Figure 6. Screen capture of the distractor task software. The subject reads the displayed sentence aloud, and a new one appears upon completion.

This task was meant to reasonably distract the users attention from the main gauges, since concentrating solely on them would not be a realistic situation. We did not have a mechanism to quantifiably judge "driving" performance.

3.4.2 Graphical Dashboard Simulation

A screen capture of the graphical dashboard simulation (GDS) software is shown in Figure 7. This software was designed to simulate the dashboard of a car, generate "problem events" in the driving environment, log user responses to the problems, and control the pneumatic pump for generating haptic stimuli.

The GDS worked as follows. The user was presented with 18 gauges, divided into three groups of six gauges. For purposes of subject identification, these groups were distinguished by color: one blue, one yellow, and one red. Each gauge had two states, "normal" and "error". In the normal state, the gauge's pointer is in the upper white half of the gauge; in an error state, the pointer is in the lower gray half of the gauge. All gauges moved constantly in both error and non-error states at random speeds.

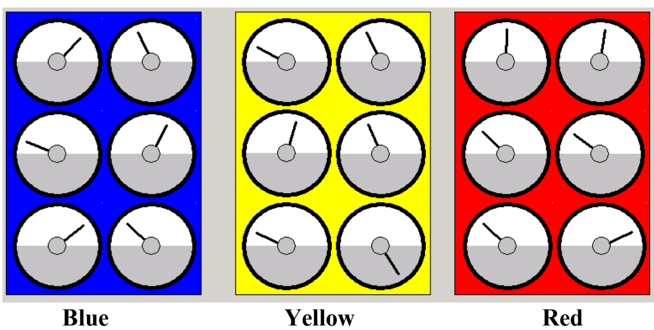

Figure 7. GUI representing a vehicle dashboard

The GDS software was programmed to send one gauge at a time into its "error" state. The time between errors was randomized. The subject was expected to press a function key corresponding to the color of the gauge in error whenever they realized that the gauge was in error. This task is meant to be an abstract representation of a problem in a vehicle, such as speed too high, engine problem, low fuel level etc.

In addition to displaying the GUI, the "Dashboard" software also recorded and logged the user response to an error and controlled the pneumatic pump's DC motor. The data recorded was:

- Response time.
- Type of response: correct, incorrect or no response.
- Set of gauges that was triggered. i.e. Red, blue or yellow.

3.5 Experiment Setup

Two computers were used for the experiment, one that hosted the GUI/Control software to control the haptic feedback and the GUI, and the second that hosted the distractor task. (Figure 1)

The subjects were instructed to place their right hand on the steering wheel between the two red marks. This hand was used to sense the haptic stimuli produced by the pneumatic display. The subject's left hand was placed near the function keys of the keyboard. The function keys were outlined in the same colors as the gauges on the GUI, and were used to identify the gauge set containing the gauge in the "error" condition.

As Fig. 1 shows, the subject was also required to wear a set of ear defenders equipped with headphones. White noise was played over the headphones to ensure that the noise created by the pneumatic pump and of the surrounding environment would not be audible. As well, room dividers were used to reduce the effect of uncontrolled visible distractions from the surrounding environment.

4. THE EXPERIMENTS

User testing was conducted using the setup described in the previous sections. Each subject conducted two experiments that are described below.

For both experiments, the subject was instructed to read sentences from the upper computer screen (see Fig. 6) through the duration of the experiment. Screen text was presented one sentence at a time and progressed at a rate the subject could comfortably read.

The subject was also instructed to monitor the gauges on the lower monitor (Fig. 7) and told that any gauge could go into "abnormal" condition at any time. When a gauge did go abnormal (at random intervals), the user could see it go into the lower gray region. 50% of the time the user was provided a haptic stimulus in the form of a fixed frequency pulsation of the steering wheel. The user was instructed to press the function key outlined in the same color as that of the abnormal gauge. The experiment measured the subject's reaction time and whether the response was or was not correct. When the user did not respond to the stimulus after 15 seconds, the experiment continued and a time of 15 seconds was recorded for the trial.

4.1 Experiment 1

Experiment 1 was devised to evaluate whether a haptic stimulus would successfully alert the user to a possible problem and whether this would reduce the time to identify it.

A single subject session can be described as follows:

- When provided, the haptic stimulus was provided at a uniform frequency of 5 Hz, for as long as the error was present.
- The time between "errors" was randomized between 15 and 45 seconds.
- 14 "errors" were created over an elapsed time of about 12 minutes.
- 50% of the errors were accompanied by a haptic stimulus, 50% were not
- The maximum allowed time to identify an error was 15 seconds.
- The user was given the opportunity to feel the haptic stimuli prior to the commencement of the experiment. The users were given an example of the stimulus they were to receive on three separate occasions.

4.2 Experiment 2

Experiment 2 was devised to evaluate whether different frequency haptic stimuli would successfully alert the subject to a possible problem and whether this would reduce the time to correctly identify it.

A single subject session can be described as follows:

- The haptic stimulus was provided at one of three frequencies and associated with a color, block of graphical dials and keyboard keys; 2.5 (blue), 6 (yellow) and 10 (red) Hz.
- The time between "errors" was randomized between 15 and 45 seconds.
- 14 "errors" were created.
- 50% of the errors were accompanied by a haptic stimulus, 50% were not
- The maximum allowed time to identify an error was 15 seconds.
- The subject was given the opportunity to feel all three haptic stimuli prior to the commencement of the experiment. During the experiment, the subjects received each of the three different frequency sensations and their associated color three times.

In order to reduce the effect of any improvement due to learning, the order of the two experiments was selected at random for each subject. Some subjects conducted Experiment 1 first; some subjects conducted Experiment 2 first. All subjects conducted both tests once during a single session.

4.3 Subjects

Eleven subjects were used during the user testing. The subjects had the following characteristics:

- 9 Males, 2 Females
- 10 Right Handed, 1 Left Handed
- All aged 25 – 35
- None of the subjects had any experience with the apparatus before the experiment

5 RESULTS

The results for each of the two experiments are discussed below.

A subject session consisted of 2 experiments; each was composed of 14 trials. These trials were 50% haptic-visual and 50% visual alone. The order for these trials was selected randomly. Each experiment took roughly 15 minutes.

5.1 Experiment 1

Figure 8 is a graph of the average times for both the haptic and non-haptic responses for experiment 1 (single level vibratory stimulus).

As the graph shows, all 11 subjects detected and respond to an event more quickly with the haptic stimulus than without. 8 of these subjects responded substantially faster, and 3 of the subjects responded only marginally faster.

An ANOVA analysis was conducted (single factor, 2 levels, blocked on subjects) and produced a significance of 0.01% for the difference of means in the reaction times for the haptic and non-haptic cases. There was a mean response time of 2.6 seconds for the haptic case, and 5.0 seconds for the non-haptic case over all subjects. This corresponds to an improvement of 47%.

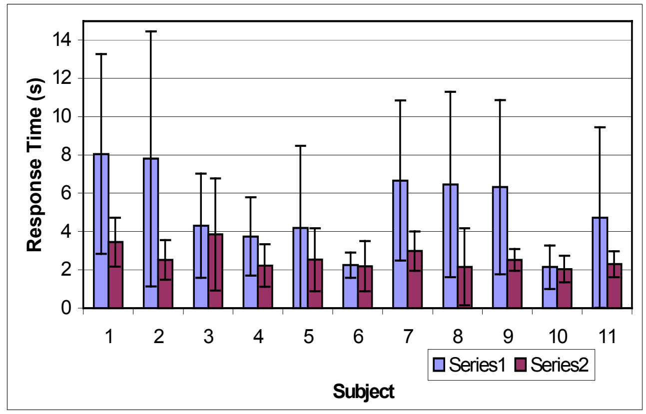

Figure 8. Experiment 1 results: Average reaction times with single level of haptic feedback. Each bar is the average of 15 values.

The number of missed or incorrect responses was also recorded and analyzed for both the haptic and non-haptic stimuli. They are summarized in the Table 1.

Subject	# Of Missed Responses (non-haptic)	# Of Incorrect Responses (non-haptic)	# Of Missed Responses (haptic)	# Of Incorrect Responses (haptic)
1	2	0	0	0
2	2	0	1	0
3	0	0	0	0
4	0	0	0	0
5	0	0	0	0
6	0	1	0	0
7	0	0	0	0
8	1	0	0	4
9	1	0	0	0
10	0	1	0	0
11	1	0	0	0
Total	**7**	**2**	**1**	**4**

Table 1. Missed and incorrect responses for test 1. Missed responses are those where the user did not notice the "error" in 15 seconds. Incorrect responses are those in which the user did notice the error, but responded with an incorrect key.

5.2 Experiment 2

Figure 9 is a graph of the average response times for both the haptic and non-haptic responses for experiment 2 (three-level vibratory stimulus). Most subjects performed significantly better in the haptic case; one subject (#4) performed slightly better in the non-haptic case.

An ANOVA analysis was conducted on the results. A mean response time of 1.9 seconds was obtained for the haptic case and 6.5 seconds for the non-haptic case over all subjects. This corresponds to an improvement of 71% in response times for the

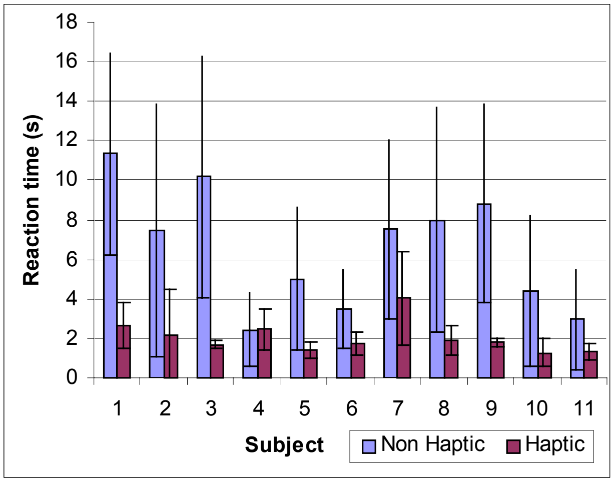

Figure 9. Experiment 2 results: Average reaction times with three levels of haptic feedback. Each bar is the average of 15 values.

haptic case. The ANOVA gave 0.01% significance on the Haptic/non-haptic factor, indicating that the results were very significant. It is interesting to note that the number of missed responses in the non-haptic case is almost double that of Experiment 1. This is discussed further in the comparison of the 2 experiments.

The number of missed or incorrect responses was also recorded and analyzed for both the haptic and non-haptic stimuli. They are summarized in the Table 2.

Subject	# Of Missed Responses (non-haptic)	# Of Incorrect Responses (non-haptic)	# Of Missed Responses (haptic)	# Of Incorrect Responses (haptic)
1	4	0	0	0
2	2	0	0	0
3	3	0	0	0
4	0	0	0	0
5	0	0	0	1
6	0	0	0	0
7	0	0	0	0
8	2	1	0	0
9	2	0	0	3
10	0	0	0	1
11	0	0	0	0
Total	**13**	**1**	**0**	**5**

Table 2. Missed and incorrect responses for test 2. . Missed responses are those where the user did not notice the "error" in 15 seconds. Incorrect responses are those in which the user did notice the error, but responded with an incorrect key.

5.3 Comparison of the 2 Experiments

The results of both experiments were compared to investigate the effect of three different levels of vibratory stimulus versus a single frequency of vibratory stimulus. First, the response times for the haptic case were plotted from both experiments. Figure 10 shows the results.

In almost all cases, the average response time for the experiment with three levels of vibratory stimulus produced a lower response time than that of the single level. Only two subjects reacted more quickly to the single level haptic stimuli, and for one of those subjects the improvement was only marginal.

This result suggests that under these conditions, the 3 levels of haptic stimulus successfully provided information to aid the user in identifying the error (i.e. whether it was a blue, yellow, or red "error"); however, individual differences exist and require further examination. This also suggests a limitation in the experiment design, i.e. we were not able to subdivide the times required to:

- Notice an error.
- Identify the colored block the error is in.
- Respond. (Identify the keyboard keys to be pressed.)

Finally, the non-haptic cases (i.e., trials in which no haptic stimuli was presented) were compared for the two experiments. Figure 11 shows these results.

It would be expected that the performance in the 2 experiments might be comparable, since the user is receiving identical information in these trials. However, it is interesting to note that for the majority of subjects, the response time in the non-haptic trials was lower for experiment 1 (1 level of vibratory stimulus) than for experiment 2 (3 levels of vibratory stimulus). The number of missed responses for experiment 2's non-haptic stimulus is almost double that of experiment 1. A possible explanation for this is that the subjects relied more on the haptic stimulus when provided with more haptic information. This reasoning was not part of our initial hypothesis, however, and the experiments were not designed to specifically test this.

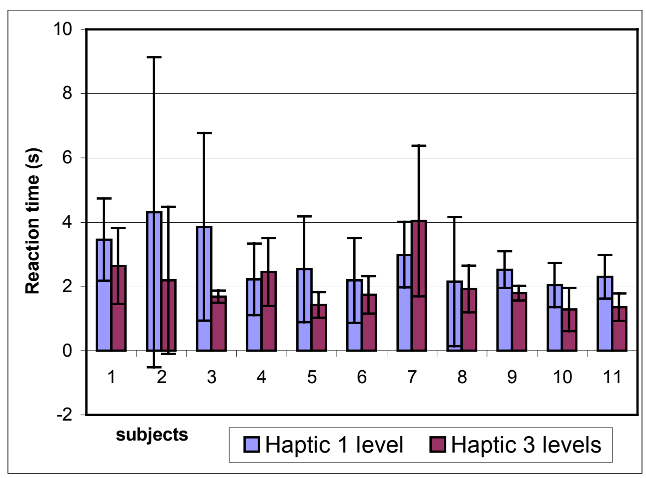

Figure 10. Comparison of responses to haptic stimuli in experiment 1 and 2: Average reaction times for one and three levels of haptic feedback. Each bar is the average of 15 values.

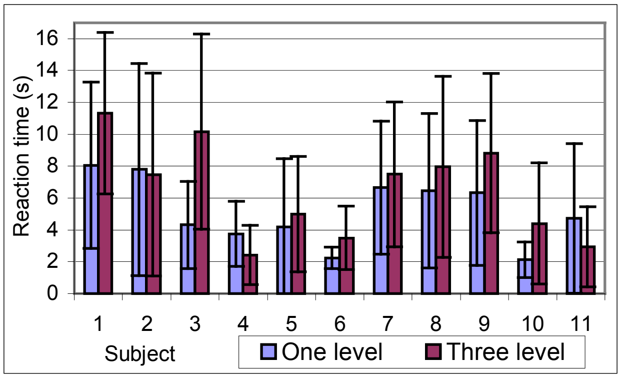

Figure 11. Comparison of responses to non-haptic stimuli in experiment 1 and 2. Average reaction times to non-haptic stimulus. Each bar is the average of 15 values.

6 CONCLUSIONS

The experiments conducted in this project yielded a number of conclusions. First and foremost, results suggest that haptic feedback could play a valuable role in driver notification and alerting in sensory overloaded conditions. This is supported by the consistent reduction in response times in both experiments 1 and 2 when a haptic stimulus was present.

The next major conclusion of this work is that 3 levels of haptic stimuli do in fact provide valuable feedback to improve identification of a problem. This conclusion is supported by the consistent reduction in response times for the haptic cases in experiment 2 over those in experiment 1. This of course assumes that the user is familiar with the form of the haptic message (in our case frequency levels) and has experience interpreting these messages.

As illustrated by Tables 1 and 2, the haptic stimuli significantly reduced the number of missed responses. This conclusion is useful because it implies that a haptic stimulus can draw attention to a problem that may have otherwise gone unnoticed. Of course, in our simulated environment the maximum time allowed to notice a response was 15 seconds, which could be too short or too long in an actual environment. Also, one can imagine situations when salient haptic stimuli could actually divert attention from where it is most required; this proposition requires further testing in a more sophisticated environment.

The time of response for the non-haptic errors was greater for experiment 2 than experiment 1. We conjecture that this is caused because of a higher reliance on the haptic stimuli when more information is provided to the subject.

There were, however, a few problems with the experimental procedure that could be worked out in future studies. The most obvious of these is that the primary driving task was not completely typical of a driving environment. Although we feel that our distractor test was adequate for what we intended to test, perhaps more realistic results would be possible if a different distractor task such as a driving simulator is used.

7 FUTURE WORK

Understand the basis of an effective driving simulation, what parameters need to be recreated in order to effectively test interface concepts. Develop a method to effectively measure the performance of a driving test and the amount of attention "lost" to the haptic stimuli applied.

The final recommendation for future work involves the construction of the pneumatic pump. For these tests, we adopted a simplified crankshaft style pump design. This design did not allow amplitude and frequency of the vibratory stimulus to be independently controlled. It would be useful to be able to independently control frequency and amplitude of the stimulus in order to fully exploit the expressiveness of the pneumatic display. A rack-and-pinion type design, together with a DC motor equipped with an optical encoder would probably accomplish this goal quite satisfactorily.

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