Assessing the Benefits of Multimodal Feedback on Dual-Task Performance under Demanding Conditions

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ABSTRACT

The last few years have seen the release of an increasing number of new IT-related devices into the marketplace that have started to utilize tactile feedback. These include those devices incorporating a touch screen that make multimodal feedback incorporating the delivery of two or more sensory modalities possible. The commonly-held view is that the use of such multimodal (or multisensory) feedback, involving the presentation of information to two or more sensory modalities ought, if anything, to improve the usability, performance, and satisfaction of the interface. In particular, an especially beneficial effect of multimodal feedback might be expected in those situations that are highly perceptually and/or cognitively demanding, such as driving a car or monitoring a complex system. In the present study, we examined the potential beneficial effect of the multimodal feedback provided by a touch screen on participants' performance in a perceptually demanding dual-task situation. We compared unimodal (visual) feedback with various kinds of multimodal (bimodal and trimodal) feedback. In addition, we also investigated the consequences of varying the intensity and number of multimodal feedback signals that were presented on driver performance (Experiment 2). Overall, the results of the two experiments reported here show that the presentation of multimodal feedback results in enhanced performance and more pronounced benefits as the intensity of the feedback signals presented to the different modalities is increased.

Categories and Subject Descriptors

H.5.2 [**User Interfaces**]: Haptic I/O, Auditory (non-speech) feedback, User-centered design.

General Terms

Human Factors, Design, Experimentation.

Keywords

Multimodal user interface, Multimodal feedback, Crossmodal interaction.

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1. INTRODUCTION

The last few years have seen the introduction of many different IT-related devices, such as mobile phones, PDAs, car navigation displays, and MP3 players that incorporate a touch screen. One potential limitation associated with the use of such devices is that a user's idiosyncratic interaction with the device may give rise to unreliable sensory feedback. For this reason, users may need additional visual feedback in order to confirm the consequences of their actions. Consequently, a number of researchers have attempted to facilitate a user's ability to hit a target by providing tactile feedback [1-4]. For instance, when users press a certain button to indicate a particular letter, tactile feedback concerning the button click can provide confirmatory evidence to a user and hence potentially increase the accuracy of their behaviour (and perhaps also their user satisfaction) while at the same time potentially reducing the cognitive load. In particular, given that the majority of tasks generally require primarily visual information processing, assistance from non-visual (i.e., crossmodal) feedback may be helpful to enable a driver (or other interface operator) to use a device without increasing the visual load [5-8]. For instance, given that the presentation of crossmodal feedback (such as sound and vibration) can help to reduce a driver's visual attentional load or act as a substitute for vision, a driver might be able to perform additional (secondary) visual task such as operating a car navigation screen in peripheral vision while keeping his/her eyes on the road ahead.

However, the results of earlier basic research on the nature of crossmodal interactions in information processing have suggested that the effect of tactile feedback might sometimes be masked because of a user's normal movements in realistic situations [9-11]. For example, in a driving situation, a moving car will usually generate a certain amount of background vibration. Just as for the case of tactile feedback, auditory feedback also has the possibility of being masked by background auditory noise or by the radio [12-14]. Given the possibility that a driver (or other interface operator) might miss feedback that happens to be presented in just a single sensory modality, the hope is that multimodal (or multisensory) feedback using two or more modalities could provide users with confirmatory or redundant information without overload and without any loss of a person's ability to process information [12-14]. In fact, several recent studies have shown that multisensory cues appear able to capture an interface operator's spatial attention no matter what else they may happen to be doing at the same time [33, 38].

Given the rapid increase in the use of computers and information technology, there is clearly an urgent need for the development of more effective and intuitive user interfaces. In

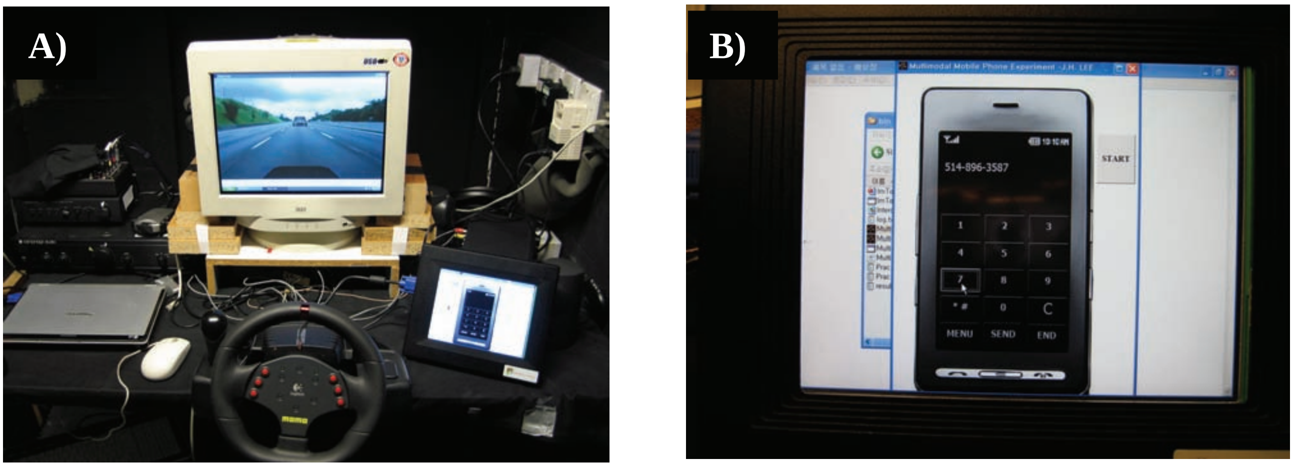

Figure 1. The left panel (A) shows the experimental set-up involving the primary task of avoiding an approaching car and the secondary task of using a mobile phone; The right panel (B) shows the touch screen device and experimental mobile phone program.

particular, to pursue more efficient and flexible human-computer interaction, a growing body of research now highlights the widespread interest in multimodal user interface design that has emerged in recent years [18]. According to the results of various behavioral and cognitive neuroscience studies, multimodal interactions occur in many different aspects of human information processing and can facilitate perceptual and cognitive processing when the stimuli in different modalities are presented in temporal and/or spatial coincidence [13, 15, 19]. Therefore, multimodal user interfaces that provide congruent combinations of signals from different sensory modalities might be expected to have a particularly beneficial effect on user behaviour/performance in those situations that are perceptually and/or cognitively highly-demanding (though see [20, 21] for the null effects of multisensory as compared to unisensory feedback reported in certain studies).

In order to investigate these questions, we conducted two experiments designed to compare unimodal (visual) and multimodal feedback (auditory + visual, tactile + visual, & auditory + tactile + visual) in response to button click events on a touch screen device. In a second experiment, we investigated whether different types of multimodal feedback (varying in terms of the intensity and number of multimodal feedback signals that were provided) would be differentially effective in terms of their ability to facilitate participants' behavioral responses. In particular, by taking a dual-task situation that requires a person to divide their attention, the participants were placed in a highly demanding situation. In this difficult task, we were able to investigate participants' responses on the driving task (involving car avoidance) and on a range of touch screen mobile phone tasks). In addition to people's objective performance, we also measured subjective workload as a function of the type of feedback that was presented using the NASA-TLX [22]. This measure was taken because it has been argued that the subjective evaluation of task difficulty may be just as important in terms of measuring (and evaluating) usability as objective behavioural performance measures [23].

2. EXPERIMENT 1

In order to examine the potential beneficial effect of multimodal (or multisensory) feedback in a highly-demanding dual-task setting consisting of a moving car avoidance task (primary task) and a touch screen mobile phone task (secondary task), we compared unimodal visual feedback with various kinds of multimodal feedback (involving the simultaneous stimulation of either 2 or 3 different sensory modalities) in response to the clicking of a button on a touch screen device by participants.

2.1 Methods

2.1.1 Participants

Eight university students (6 female; mean age 23 years, age range 21-28 years) with normal or corrected-to-normal vision and hearing took part in Experiment 1. Three of the participants were left-handed by self-report and all gave their informed consent prior to taking part in the study. All of the participants were naïve as to the purposes of the study which took approximately 30 minutes to complete.

2.1.2 Apparatus and Stimuli

Each participant was individually seated in an acoustically-isolated booth and instructed to try and avoid the approaching car that was displayed on the screen in front of them by turning a Logitech® Momo Racing® Force Feedback Wheel (Logitech Inc.) mounted on a desk situated directly in front of them (see Figure 1A). The stimuli in the driving task were presented on a 19 inch CRT monitor (refresh rate of 75Hz) placed 50 cm from the steering wheel. An 8.4 inch LCD touch monitor with tactile feedback (Immersion® TouchSense® Touchscreen Demonstrator; 60 Hz refresh rate) provided the display that was used to present the mobile phone task (see Figure 1B). Auditory feedback was presented from a loudspeaker cone situated directly behind the back of the touch screen device. Auditory feedback was synthesized at 16-bit & 44.1 kHz and saved in WAV format. The auditory feedback consisted of a 355 Hz bell sound presented for 150 ms at approximately 70 dB as measured from the participant's ear position. Tactile feedback (50 Hz) from the touch screen was presented for 50 ms from four actuators mounted inside the touch screen device (index number 17 of the built-in Tactile Effects; for details, see Immersion® TouchSense® SDK Programming Guide, 2006).

The tactile feedback was presented at a clearly suprathreshold level.

2.1.3 Experimental Design

There was one within-participants factor: The Type of feedback (4 levels): Visual Only (V), Tactile + Visual (TV), Auditory + Visual (AV), and Auditory + Tactile + Visual (ATV). Each participant completed 10 mobile phone task trials with each type of feedback, with the order of presentation of the four types of feedback counterbalanced across participants. Each participant therefore completed a total of 40 mobile phone trials. The 3 telephone tasks that the participants had to perform consisted of dialing a telephone number on the keypad (4 trials), creating a text message (2 trials), and selecting a name from the contact list (4 trials). If the participants made a mistake on the telephone task, they could delete their last key press by pressing a 'clear' button on the mobile phone keypad. The participants had to press 15 keys in order to complete the telephone number dialing task, 16 keys in order to create the text message, and 6 keypresses were required in order to select a name from the contact list. These tasks were performed in a random order in each feedback condition.

2.1.4 Procedure

In the driving task, the participants had to try and avoid an approaching car that moved randomly to the left or right of the screen once every 4.5 seconds. The participants were instructed to turn the steering wheel to the right as quickly as possible whenever the approaching car moved to the left (and vice versa when the car moved to the other side of the screen). The participants' reaction time (RT) on each trial was measured from the moment when the lead car on the screen moved to one or other side until a 60 degree turn of the steering wheel was recorded. The participants were instructed to perform the mobile phone task at the same time as they performed the driving task. In the mobile phone task, the participants had to make and send a call or message using the touch screen device. The specific task to be completed on each trial was shown on the touch screen itself. The participants were informed that they should divide their attention so as to perform both tasks as rapidly and accurately as possible. In addition, after the participants had completed the 10 trials with each type of feedback, they completed the NASA-TLX in order to measure the subjective workload associated with the immediately preceding feedback condition [22].

2.2 Results: Behavioural Performance

Two measures of participants' behavioural performance were calculated: The mean car avoidance RT on those trials in which they successfully avoided the car in front (which they were able to do on 97% of the trials on average), and the mean time taken by participants to complete the touch screen tasks. Analysis of the mean car avoidance RT data revealed that the participants in Experiment 1 responded significantly more rapidly when given trimodal feedback than when given unimodal visual feedback [*p*<.05, 1-tailed pairwise comparisons, the use of a 1-tailed test is justified given our prediction that multimodal feedback would result in better performance than unimodal feedback]. Visual inspection of Figure 2 shows that participants' performance in the bimodal feedback trials fell in-between that observed in the unimodal and trimodal feedback conditions. However, none of the other pairwise comparisons in this data analysis reached statistical significance.

A similar analysis of the mean latency of participants' responses to complete the touch screen trials revealed that they responded significantly more rapidly when given trimodal

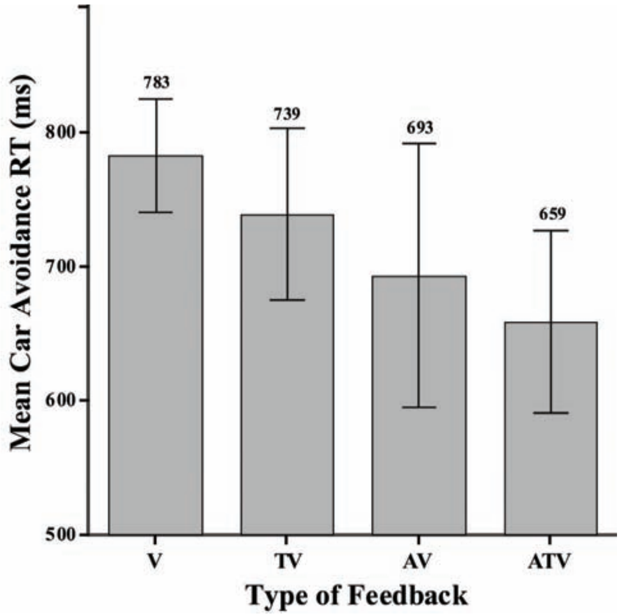

Figure 2. Mean response time (ms) in each trial in which the participants successfully avoided the approaching car plotted as a function of the type of feedback presented on the secondary phone task; V = Visual Only, TV = Tactile + Visual, AV = Auditory + Visual, and ATV = Auditory + Tactile + Visual. The error bars show the standard errors of the means.

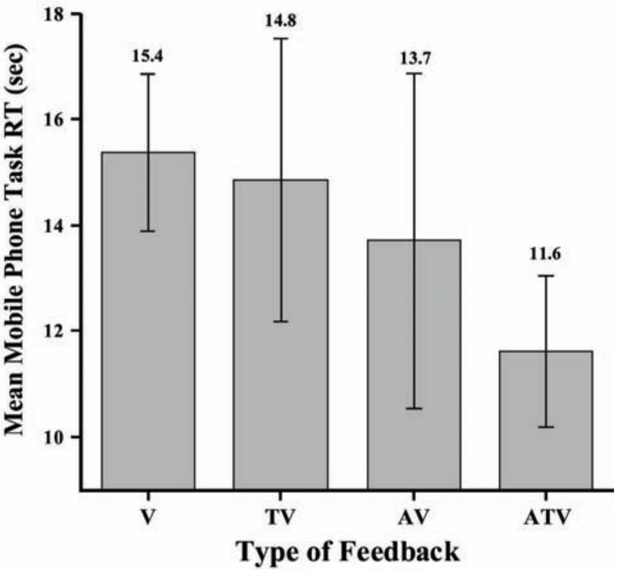

Figure 3. Mean RT on the mobile phone touch screen task plotted as a function of the type of feedback presented; V = Visual Only, TV = Tactile + Visual, AV = Auditory + Visual, and ATV = Auditory + Tactile + Visual. The error bars represent the standard errors of the means.

feedback than when given unimodal visual feedback [*p*<.05], with intermediate performance once again being reported on the bimodal feedback trials (see Figure 3).

The results of the analysis of the behavioral data therefore demonstrate that the participants were able to perform both the car avoidance and mobile phone tasks more rapidly when they were given trimodal sensory feedback (including auditory, tactile, and visual stimulation) than when they were only provided with unimodal visual feedback. Bimodal (as compared to unimodal) feedback also appeared to facilitate performance to a certain extent, although the comparisons with the unimodal feedback data failed to reach significance (presumably due to the relatively small number of participants who were tested). There was no difference in the accuracy of participants' performance in the mobile phone touch screen task (which our participants performed correctly on 98% of the trials). These results therefore rule out a speed-accuracy trade-off account of the RT facilitation observed in Experiment 1 (see [24]).

It has been argued that any intervention capable of reducing a driver's response latencies by 500 ms would likely reduce front-to-rear-end (FTRE) collisions (which constitute the most common type of car accident; [25, 26]) by as much as 60% (e.g., see [27, 28]). Importantly, we were able to show that the participants in Experiment 1 responded to the car avoidance task an average of 124 ms faster when provided with trimodal feedback, rather than with just unimodal visual feedback. To put this reduction in stopping latencies into perspective, it equates to a reduction in the distance needed to stop a car when driving at 80 Km/h of approximately 3-meters. Such results are particularly important given Strayer and Johnston's (2001) finding that drivers who use a mobile phone while driving may actually double their risk of having a FTRE collision while at the wheel [29].

2.3 Results: NASA-TLX workload

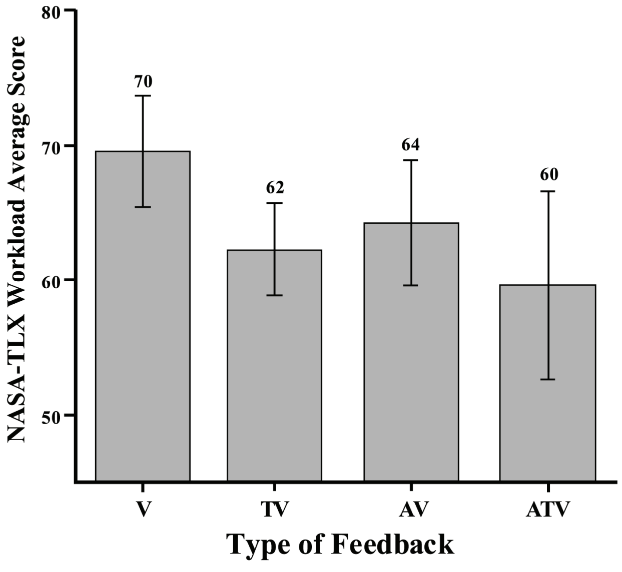

Figure 4. Average NASA-TLX workload score (scores can range from 0 ~ 100) plotted as a function of the type of feedback; V = Visual Only, TV = Tactile + Visual, AV = Auditory + Visual, and ATV = Auditory + Tactile + Visual. Note that the higher the score, the higher the subjective workload. The error bars represent the standard errors of the means.

A similar analysis of the NASA-TLX workload data (collected from all but 1 of the participants) revealed that the participants rated the subjective workload associated with the trimodal feedback touch-screen task as being numerically somewhat lower than when they were given unimodal visual feedback, although this difference just failed to reach statistical significance [*p*=.085] (see Figure 4). Interestingly, however, the introduction of bimodal (relative to unimodal) feedback was found to result in a significant reduction in the subjective load [AV, *p*<.01; TV, *p*<.05]. These results therefore clearly show that multimodal feedback (i.e., feedback that includes the stimulation of two or more sensory modalities) can have a beneficial effect on subjective measurements of workload as well as on the more objectives measures of participants' behavioural performance.

3. EXPERIMENT 2

The results of Experiment 1 highlight the potentially beneficial effect of multimodal (or multisensory) feedback on driver performance in a simulated driving task. However, in order to deliver such multisensory feedback more effectively, we decided to further investigate the properties that such multimodal feedback signals ought to incorporate in order to maximize the beneficial effect of the presentation of such signals on human task performance [30]. Therefore, in our next experiment, we compared the effect of changing the intensity (low vs. high) of the tactile feedback and of varying the number of tactile feedback signals presented (single vs. dual pulsed presentation) in response to the button click events on the touch screen device on participants' performance when tested in the demanding dual-task setting developed in Experiment 1.

3.1 Methods

3.1.1 Participants

Fourteen university students (9 female; mean age 23 years, age range 19-34 years) with normal or corrected-to-normal vision and hearing took part in Experiment 2. Two of the participants were left-handed by self-report and all of the participants gave their informed consent prior to taking part in the study. All of the participants were naïve as to the purposes of the study which lasted for approximately 20 minutes.

3.1.2 Apparatus and Stimuli

These were exactly the same as for Experiment 1 with the exception that the intensity and the number of multimodal

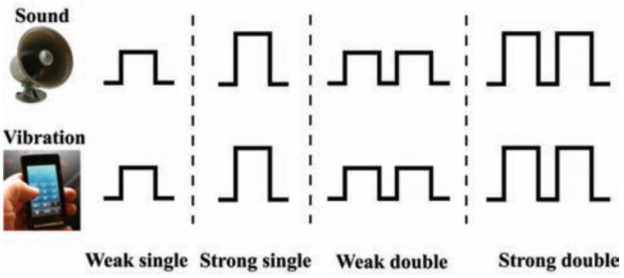

Figure 5. The various kinds of multimodal feedback presented in Experiment 2; Weak single: weak single auditory & vibrotactile signal; Strong single: strong single auditory & vibrotactile signal; Weak double: weak double auditory & vibrotactile signal; & Strong double: strong double auditory & vibrotactile signal.

feedback signals were now varied (see Figure 5). In Experiment 2, we compared participants' performance following the presentation of various different numbers and intensities of multimodal feedback signals. All of the auditory feedback signals were synthesized at 16-bit & 44.1 kHz and saved in WAV format. The single auditory feedback signal was presented for 50 ms (as compared to 150 ms in Experiment 1), while the double auditory feedback consisted of the sequential presentation of two 50 ms tones separated by a 10 ms empty interval. The weak auditory feedback differed from the strong auditory feedback in terms of the intensity of the signal: it was presented at approximately 60 dB, as compared to 70 dB for the strong signal. Just as for the auditory feedback, four types of vibrotactile feedback were presented, these varied in the intensity and number of signals that were presented. The difference between strong and weak tactile feedback was a relative magnitude of 2 (relative magnitudes of 10 vs. 8, respectively; for details, see Immersion® TouchSense® SDK Programming Guide, 2006, p. 113).

3.1.3 Experimental Design

There were two within-participant factors: The intensity of the multimodal feedback (weak vs. strong), and the number of multimodal feedback signals that were presented (single vs. double). The combination of multimodal feedback was varied on a trial-by-trial basis with the order of presentation of the 4 types of feedback counterbalanced across participants. Each participant completed a total of 20 trials including 5 mobile telephone task trials (2 trials in making a call using the number key, 2 trials in making a text message, and 1 trial in selecting a name from the contact list) with each of the 4 types of multimodal feedback.

3.1.4 Procedure

The procedure was identical to that reported in Experiment 1. The NASA-TLX questionnaire was no longer presented in our second experiment.

3.2 Results

Analysis of the mean car avoidance RTs on those trials in which the participants successfully avoided the lead car (which they were able to do on 97% of the trials) revealed a statistically significant main effect of the intensity of the multimodal feedback signal [*F*(1,13)=4.82, *p*<.05], with the participants responding more rapidly on the car avoidance task when stronger feedback was presented on the mobile phone task than when weaker feedback was presented (mean RT = 729 vs. 817ms, respectively). There was no main effect of the number of multimodal feedback signals that were presented [*F*(1,13)<1, *n.s.*] (see Figure 6). Next, we conducted pairwise comparisons on the basis of our prediction that strong and/or double multimodal feedback would have a more positive effect on performance than the weak and/or single multimodal feedback, a comparison of weak double and strong double multimodal feedback revealed a statistically significant difference [*p*<.05]. Similarly, a comparison of weak single and strong double multimodal feedback also revealed a statistically significant difference as well [*p*<.05].

A similar analysis of the mean latency of participants' responses on the touch screen task (which they performed correctly on 98% of these trials) once again revealed a statistically significant main effect of the intensity of the multimodal feedback signal [*F*(1,13)=12.69, *p*<.005] (see Figure 7). There was, however, no significant main effect of the number of multimodal feedback signals that were presented [*F*(1,13)<1, *n.s.*]. The interaction between the intensity and number of multimodal feedback signals approached significance [*F*(1,13)=2.04, *p*=.088], suggesting that participants responded more rapidly when the feedback signal consisted of a strong double signal than when only a single stimulus was presented, while when the feedback signal was

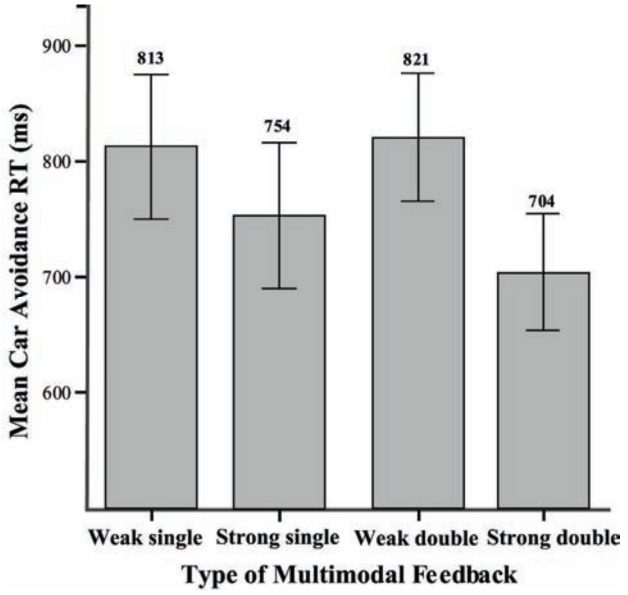

Figure 6. Mean RT (ms) from those trials in which the participants successfully avoided the approaching car plotted as a function of the intensity and the number of multimodal feedback signals presented on the secondary phone task. The error bars show the standard errors of the means.

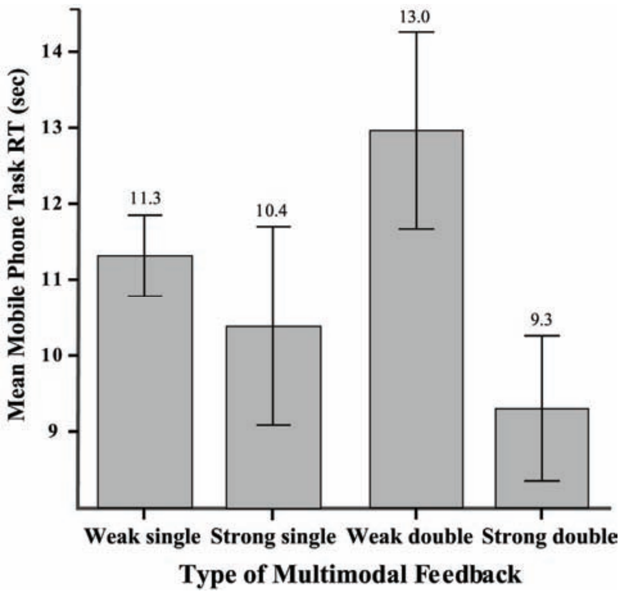

Figure 7. Mean RT (sec) on the mobile phone touch screen task as a function of the intensity and the number of multimodal feedback presented on the secondary phone task. The error bars show the standard errors of the means.

weak, double simulation resulted in slower performance. Meanwhile, pairwise comparisons also revealed a significant difference between the weak and strong double stimulation feedback trials [*p*<.005]. Comparison of the weak single and strong double multimodal feedback and comparison of the strong single and weak double multimodal feedback revealed statistically significant differences [both *p*<.05]. Importantly, however, there was no difference in the accuracy of participants' performance on the mobile phone touch screen task (which participants performed correctly on 98% of the trials). Therefore, the analysis of the results of Experiment 2 once again ruled out a speed-accuracy trade-off account of the RT data (see [24]).

In summary, the participants in Experiment 2 responded significantly more rapidly (and no less accurately) in the car avoidance task when they were provided with strong double multimodal feedback signals in the telephone task. The participants also performed the telephone tasks (e.g., making calls and typing messages using the touch screen device) more rapidly when presented with the stronger double multimodal feedback. These two results therefore demonstrate that the properties of the multimodal feedback signal, including both the intensity and/or number of multimodal feedback signals that are presented to the user of a tactile/haptic interface can have a significant effect on a user's information processing and behavioural responses. In other words, the beneficial effects of well-designed multimodal feedback appear capable of facilitating a users' ability to successfully dual-task without overly burdening their cognitive/attentional resources.

4. CONCLUSIONS

The 2 experiments reported in the present study were designed to investigate the potential beneficial effect on human performance that may be associated with the presentation of multimodal (as opposed to unimodal) feedback when using a touch screen device that provided tactile feedback in a task having a relatively high perceptual load [31]. These results clearly show that both objective and subjective measures of driver performance were enhanced by the presentation of trimodal (as opposed to unimodal) feedback, with performance in the bimodal feedback conditions typically falling midway between that seen in the other two conditions.

Considering the cognitive science and experimental psychology literature on multisensory perception and intermodal coordination (see [32]), these results presumably reflect the fact that multimodal feedback can maximize human cognitive and physical abilities relating to attention, working memory, and decision making [15, 33]. Moreover, we observed that presenting more intense multimodal feedback resulted in a larger facilitation of participants' performance. Taken together, the results reported here suggest that we should present the information from multiple sensory modalities in a manner that is compatible with a user's perceptual constraints (and preferences), the context, and the functionality of the system concerned [13, 16]. In particular, the results of our study go beyond previous research by testing a larger range of feedback modality combinations in the practical context of the use of a touch screen while driving. It should be noted that the failure to demonstrate any benefit of bimodal over unimodal feedback in a car driving situation that has been reported in several recent studies may have been due to the spatial disparity introduced between the signals presented in the various different modalities. In this regard it is important to note that all of the feedback signals presented in the present study came from the same spatial location, and this may help to explain why such a beneficial effect was observed on driver performance [20, 34]. It is also worth noting that the trimodal feedback was found to be particularly effective in our study.

Future research should further investigate what constitutes the most effective and satisfactory combination of modalities and stimulus parameters for feedback by examining the various different properties of multimodal feedback, such as their temporal synchrony (see [35-37]) and spatial coincidence (see above, [38]). One particularly interesting question for future research will be to determine whether optimal driver responses to multimodal feedback come from the simultaneous presentation of feedback in all three modalities, or whether instead such trimodal feedback signals can be made even more effective by the slight desynchronization of the component sensory signals [35, 37]. The idea here is that given the differences in the latency of transduction of signals in different sensory modalities ([39]), it might prove advantageous to desynchronize the component unimodal signals in order to try and ensure that all components of the multisensory warning signal arrive at those neural centers in the brain that control orienting and attention (such as the superior colliculus) at the same time.

Finally, it is worth noting one of the potential limitations in terms of the interpretation of the results presented here comes from the fact that we only tested relatively young participants (ranging in age from 19-34 years). It will therefore be an interesting question for future research to determine whether the benefits of multimodal (or multisensory) feedback will also be evident in older individuals. This is a particularly important issue given the rapidly growing number of older drivers on the roads [41, 42]. In fact, the available cognitive neuroscience evidence suggests that older people may, in fact, benefit even more from multisensory (as opposed to unisensory) stimulation than younger people [43-47].

5. ACKNOWLEDGEMENTS

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