

Multimodal Feedback: Establishing a performance baseline for improved access by individuals with visual impairments

Holly S. Vitense¹, Julie A. Jacko² and V. Kathlene Emery²

¹Department of Industrial Engineering
University of Wisconsin-Madison
1513 University Avenue
Madison, WI 53706
+1 608 262 6240
hsbautsch@students.wisc.edu

²School of Industrial & Systems Engineering
Georgia Institute of Technology
765 Ferst Drive
Atlanta, GA 30332-0205
+1 404 894 2300
jacko@isye.gatech.edu

ABSTRACT

Multimodal interfaces have the potential to enhance a user's overall performance, especially when one perceptual channel, such as vision, is compromised. This research investigated how unimodal, bimodal, and trimodal feedback affected the performance of fully sighted users. Limited research exists that investigates how fully sighted users react to multimodal feedback forms, and to-date even less research is available that has investigated how users with visual impairments respond to multiple forms of feedback. A complex direct manipulation task, consisting of a series of search and selection drag-and-drop subtasks, was evaluated in this study. The multiple forms of feedback investigated were auditory, haptic and visual. Each form of feedback was tested alone and in combination. User performance was assessed through measures of workload and time. Workload was measured objectively and subjectively, through the physiological measure of pupil diameter and a portion of the NASA Task Load Index (TLX) workload survey, respectively. Time was captured by a measure of how long it took to complete a particular element of the task. The results demonstrate that multimodal feedback improves the performance of fully sighted users and offers great potential to users with visual impairments. As a result, this study serves as a baseline to drive the research and development of effective feedback combinations to enhance performance for individuals with visual impairments.

Keywords

Multimodal, visual impairment, auditory, haptic, visual, feedback, and human-computer interaction

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Assets 2002, July 8-10, 2002 Edinburgh, Scotland
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INTRODUCTION

There are 10 million blind and visually impaired individuals in the United States, 1.3 million Americans who are legally blind, and 5.5 million elderly individuals who are blind or visually impaired [1]. With these growing numbers, it is imperative to consider how to assist this population in maintaining capabilities and make possible the potential to succeed within a computationally rich environment.

In computational systems and technologies, visual feedback is the most prevalent in the support of direct manipulation tasks. Since direct manipulation tasks are representative of the majority of actions performed using Graphical User Interfaces (GUIs), visual feedback is essential to maintaining effective human-computer interaction. As a result, this places individuals with visual impairments at a disadvantage, decreasing the bandwidth of information available, and thus limiting the effectiveness of their interactions. Jacko and Sears [5] cite the importance of understanding the impact of visual profiles on interaction strategies in identifying optimal system configurations. Examples of applications incorporating an understanding of low vision users are somewhat limited.

A user population with visual impairments spans a host of clinical diagnoses and resulting functional limitations [7]. Traditional assistive technologies for individuals with visual impairments have focused on augmenting and increasing the visual channel of perception through techniques such as the magnification of objects, and increasing the contrast of the colors presented. An example of this is Kline and Glinert's UnWindows VI [9]. In addition to selective magnification, UnWindows VI also kept track of mouse pointer location for a user through a stylized pair of eyes that continuously gazed in the direction of the pointer. This interface also presented the user with aural feedback to supplement the visual components. As one of the few examples of bimodal interfaces for the low

vision population, it should be noted that UnWindows VI primary means of improving accessibility was through the visual channel. With respect to the segment of the population with visual impairments that wants and needs to use their residual vision, the state of technology today offers little beyond single modality solutions. Furthermore, these solutions are heavily focused on the reinforcement of the visual sense of perception.

Fraser and Gutwin [3], in their proposed 'Framework of assistive pointers for low vision users,' introduced the idea that the presentation of different feedback forms could assist people who have visual impairments. Three modalities of feedback, 1) visual, 2) auditory, and 3) haptic, were suggested to have the capacity to better enable this segment of the user population. Working examples of multimodal feedback that assist users with low vision are rare. Many tools or system settings that exemplify the framework were not intentionally designed for individuals with low vision. In fact, the primary example used by the authors is UnWindows [9].

If a user has circumstances denying them full access through one modality, such as visual impairments, they may operate more effectively with an alternate modality, or with the combination of several modalities. This presents a need for the research and development of interfaces that integrate modalities in an effort to communicate information and system status to users who have visual impairments.

Performance Baseline for Multimodal Feedback

Limited research exists that investigates how fully sighted users react to multimodal feedback, and to-date even less has investigated how users with visual impairments respond to multiple feedback. Before design criteria for multimodal feedback can be instituted in favor of the low vision population, a baseline of performance for the fully sighted population needs to be grounded. Justification for this approach is two-fold.

First, there is a need to prove that differences exists between how fully sighted users and users with visual impairments react to, and interact with, multiple forms of feedback. This mandates the consideration of special populations within the design life cycle. Fully sighted users and users with age-related macular degeneration (AMD) have been compared with respect to visual feedback alone [6]. This empirical research revealed that differences do exist and that users with low vision need technology that considers their unique abilities. It is important to reduce differences between these user populations so that performance capabilities can be equalized.

Second, in accordance with the theories of universal access, it is useful to know how the majority of users would interact with techniques (e.g., multimodal feedback) designed to enhance accessibility for users with visual impairments. Universal access signifies that all users, regardless of their abilities, maintain effective interaction with information

technology [11]. As a result, it is critical to study multiple user populations to obtain universal access. Initial benefits of multimodal feedback need to be first established through the development of a baseline of user performance for fully sighted users. The knowledge gleaned from the baseline is then further informed by studies of different user populations, ultimately resulting in a universally accessible multimodal interface.

Multimodal interfaces have the potential to enhance users' access to, and interaction with, information technologies through an augmentation of the perceptual processes via multiple modalities. For instance, those users who have difficulty with one modality could greatly benefit from using an alternative modality, or a combination of modalities enabled by a multimodal interface. In the case of users with visual impairments, auditory and haptic modalities offer tremendous potential for contributing to effective interaction when the visual modality is engaged, or overwhelmed.

This research investigated how multimodal feedback affected the performance of fully sighted users, in an effort to establish a baseline that could eventually enhance the performance of users with visual impairments. Auditory, haptic and visual feedback were tested alone and in combination. The effects of combining two modalities (auditory/haptic, auditory/visual, and haptic/visual) and all three of these modalities (auditory/haptic/visual) together are largely untested. Identifying the affects of these combinations is important not only to fully sighted users but also users with visual impairments because of the potentially huge implications the results could have for individuals with special needs.

User performance was gauged by measures of mental workload and performance time, while feedback modalities were altered. Despite the fact that workload is not a common measure reported in the human-computer interaction literature, mental workload has long been recognized as an important element of human performance in complex systems [4]. As a result, mental workload has a direct influence over a user's ability to perform a task. This is especially true when a user's ability may already be compromised in a particular sense.

Because it is essential to uncover accessible technologies that enhance performance while not increasing workload, mental workload was measured in this study. Workload is a complex concept with many aspects; as a result, there is not a single measure that can capture all of these aspects. Therefore, it is better to use a combination of techniques than a single measure. For this reason, the research presented here examined two measures of workload to determine how multimodal feedback affected user performance. In this research both subjective and physiological objective measures, a ranking of mental demand and pupil diameter respectively, were collected.

Examining both types of workload measures provides a comprehensive measurement of workload.

Performance time was also used to gauge user performance. Performance times have long been used to measure users' abilities to complete a task. In this research a measure of target highlight time was captured.

METHODS

Participants

Thirty-two participants were selected for inclusion in this study. Their ages ranged from 21 years to 36 years. The participants were monetarily compensated for their participation. The inclusion criteria were three-fold: 1) Right-handedness: to be able to use the right handed haptic and ordinary mouse provided, 2) Corrected vision near 20/20: to be able to see the visual feedback, and 3) Near normal hearing capabilities: to be able to detect the auditory feedback generated by the computer.

Apparatus

The Auditory-Haptic-Visual (AHV) Multimodal software, a customized product developed in-house, facilitated the drag-and-drop task and the manipulation of the three modalities within a GUI. The AHV Multimodal Software was run on a Pentium 4, 2.0 GHz computer with a 21-inch color monitor set at a resolution of 1152 x 864. The participants were positioned an average 2.5 feet from the monitor. A Logitech WingMan® Force Feedback Mouse was used to provide the haptic feedback. The haptic feedback manifested itself in the form of a vibration. During treatment conditions in which the software did not, by design, provide haptic feedback the participants were instructed to use the ordinary Microsoft® mouse. A simple calibration test revealed no statistical difference between the operation of the two mice for each participant.

A physiological measure of mental workload (i.e., pupil diameter) was obtained from an eye gaze tracking system. An Applied Science Laboratory, Model ASL 501® head-mounted infrared video eye gaze tracking system was used to capture participants' eye pupil diameter.

A subjective measure of mental workload, specifically mental demand, was captured between tasks with subjective workload ranking forms developed from the NASA-TLX survey.

Procedure

The participants were given an explanation of the research and their role in the study from the experimenter. Each individual was screened to meet visual, auditory, and handedness criteria. Upon satisfaction of the criteria, the participants were given instructions on how to complete the subjective workload ranking forms. Finally, the participants received familiarization training.

Training Task

The goal of the training task was to familiarize the participants with the experimental task and each feedback

condition. By the completion of the training the participants were equally proficient with each feedback condition. Because auditory and haptic feedback are less common to interaction than visual feedback, there was a potential for biased performance in the conditions containing visual feedback. This potential for bias was eliminated by the training task. The statistical analyses run on the training task data confirmed none of the feedback conditions were statistically different with respect to participants' performance. As a result, the participants began the experimental task equally proficient in the auditory, haptic and visual feedback conditions.

Experimental Task

Once the participants completed the training task and felt comfortable with each feedback condition, they were given an explanation of the actual experimental task. Upon understanding the explanation, the participants were fitted with the head-mounted optics of the eye tracking system. They were asked to look at the AHV Multimodal computer monitor so that the eye tracking system could be calibrated. Once calibration was verified, each participant was presented with a notification screen to inform them as to what type(s) of feedback they should anticipate before every upcoming condition.

The experimental task evaluated in this study was a complex direct manipulation, similar to that used by Brewster [2]. The task consisted of a search selection drag-and-drop task. A 5x5 grid of Microsoft Word® file icons, 25 in total, appeared in the middle and upper portion of the screen while five Microsoft Office® folder target icons appeared at the bottom of the screen, as shown in Figure 1. The file and folder icons were lettered A thru E. Each participant was asked to move each lettered file icon to the folder icon with the same letter (A thru E) as 'quickly and accurately' as possible.

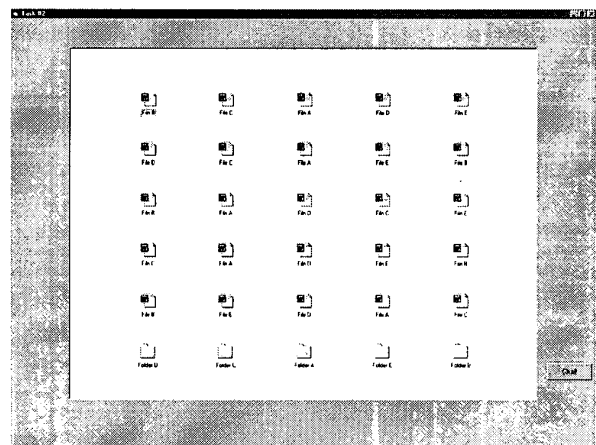


Figure 1. Experimental Task.

Upon placing a file in a folder, the lettered file icon disappeared. At that same time, a replacement file reappeared in the file's original position to serve as a

placeholder. This was done to ensure the search complexity remained consistent for the duration of the trial. The replacement files were labeled 'File X' and were immobile to avoid confusion as to which files had yet to be moved into folders. Once all the files were placed in folders, the screen was cleared and was replaced with a new arrangement of file and folder icons. The participants completed two replications of the task within each feedback condition, and then completed a workload assessment form.

The locations of source and target icons were manipulated throughout the experimental trials. The conditions for which the feedback was manipulated, varied randomly.

Experimental Design

This study was a 2x2x2 factorial, within-subject design. The independent variables were auditory feedback, haptic feedback, and visual feedback. Two categories of dependent variables were collected to capture the participants' performance, mental workload and performance time. More specifically, mental workload was captured through a subjective ranking of mental demand and an objective, physiological measure of pupil diameter. The measure for performance time consisted of target highlight time.

Each of the three independent variables (the feedback forms) had two levels: 'present' and 'absent'. An independent variable with the level 'present' indicates that the associated feedback was provided in the condition and a variable with a level 'absent' means the associated feedback was not provided. Table 1 illustrates the different variables and levels that comprise each of the eight conditions. A Latin Square design was used to counterbalance the various sequences in which the levels of the independent variables occurred [8]. This design was repeated 4 times to accommodate 32 participants.

Table 1. Experimental design: auditory, haptic and visual feedback (C denotes condition number).

AUDITORY							
Present				Absent			
HAPTIC				HAPTIC			
Present		Absent		Present		Absent	
VISUAL		VISUAL		VISUAL		VISUAL	
Present	Absent	Present	Absent	Present	Absent	Present	Absent
C8	C7	C6	C4	C5	C3	C2	C1

In one of the conditions, no feedback was provided. In three conditions, unimodal feedback (visual, haptic, and auditory) was tested. In another three conditions, bimodal feedback (haptic/visual, auditory/visual, and auditory/haptic) was tested. Lastly, a trimodal feedback (auditory/haptic/visual) was tested.

Independent Variables

The auditory feedback conditions were generated by an earcon [2]. When the participant positioned the file icon over the folder target icon, a musical tone sounded. This

sound alerted the participants to the fact that the files were indeed over the target. The same tone, representing 'move', was used for each target in order not to complicate audio feedback.

A vibration effect from the force feedback mouse provided the haptic feedback. The vibration effect can best be described as slight, quick movements produced by the haptic mouse. When the file icon was over the folder icon, the force feedback mouse vibrated. The vibration was generated by a triangle waveform for a duration of 0.30 second.

The visual feedback condition was in the form of a blue highlight. When the file icon was over the desired target, the target icon highlighted blue. This visual feedback, like the other types of feedback, signified that the participant had correctly moved the file to that particular folder. These three types of feedback, auditory, haptic and visual, were presented alone and in combination.

Dependent Variables

Mental workload and performance time were the two categories of measures collected from the participants while completing the experimental task.

Mental workload was measured subjectively, by the mental demand NASA-TLX ranking that captured how much mental activity was required (i.e., thinking, deciding, calculating, and searching, etc.) while performing the task. Mental demand was assessed for each feedback condition. This mental demand ranking gauged the participants' assessment of the underlying psychological indicators of workload associated with the experimental task, and more specifically the ability to perform the drag and drop task. After reviewing the rating scale definitions, participants gave an assessment by providing an absolute rating on a scale from 0 (no workload) to 100 (extremely high workload).

Mental workload was also measured objectively, by the physiological measure of pupil diameter. In workload-related research pertaining to usability, pupillary response has been commonly used [10]. Pupillary response, in particular pupil diameter, responds to workload. Pupil diameter closely correlates with resource demands of a large number of diverse cognitive activities [13]. Pupil diameter reaches its maximum size when memory load is presumed to be the highest [10]. The eye gaze tracking system collected pupil diameter at a rate of 60 Hz during all eight conditions. Pupil diameter was reported in units of millimeters (mm).

Performance time was captured by target highlight time (THT). This measured the time between when a participant positioned the file over the folder to when he/she released the mouse button, thus dropping the file into the folder. THT was collected every time a file was dropped into a folder. THT succinctly represents the effectiveness of feedback by measuring how long it took a participant to

recognize and interpret the various forms of feedback presented. A true measure of feedback is how quickly it conveys meaning to the user and THT is a measure of precisely that element of response time. THT was reported in seconds (s), and was captured by the computer running the AHV Multimodal software.

Statistical analyses of these measures revealed how user performance varied with respect to the type of feedback presented. Mental demand and THT were also reported in [12].

RESULTS

A general linear model, repeated measures analysis was run to analyze mental workload (mental demand and pupil diameter), and THT. The within-subject factors were auditory, haptic, and visual feedback, all at two levels, while condition order was treated as a between-subject factor.

Mental Workload – Mental Demand

A significant main effect of visual feedback ($F_{(1,24)} = 4.674$; $p < .05$) was found for mental demand. When visual feedback was provided, the level of perceived mental demand decreased. The mean mental demand ranking for the average of the conditions without visual feedback (none, auditory, haptic, auditory/haptic) was 31.92. The ranking for the average of the conditions with visual feedback (visual, auditory/visual, haptic/visual, auditory/haptic/visual) was 28.95. The scale ran low (0) to high workload (100), so the perception of mental demand decreased when visual feedback was present.

A significant three-way interaction was found between auditory, haptic, and visual feedbacks ($F_{(1,24)} = 10.579$; $p < .05$). This three-way interaction will be depicted in two, two-way illustrations shown in Figures 2 and 3. Figure 2 shows the auditory by haptic interaction with visual absent, while Figure 3 shows the interaction with visual feedback present.

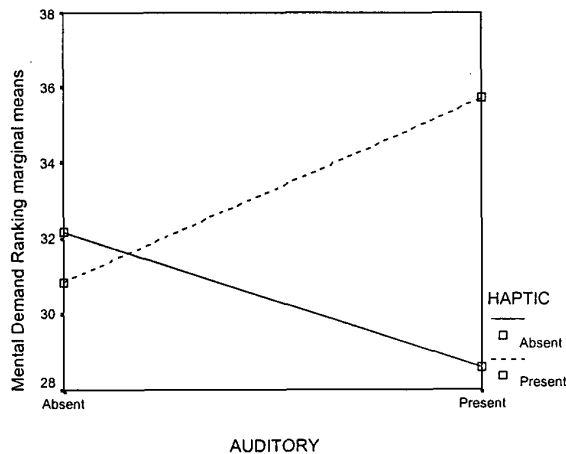


Figure 2. Auditory x Haptic interaction when visual is absent for mental demand.

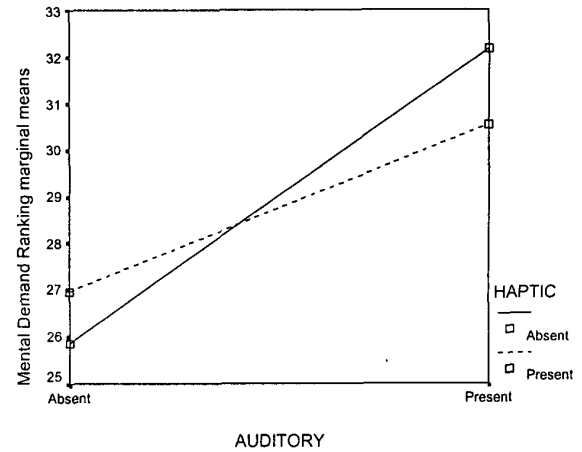


Figure 3. Auditory x Haptic interaction when visual is present for mental demand.

Auditory feedback and haptic feedback were strongly affected by the presence of visual feedback. The unimodal condition of visual feedback (mean 25.85) and the bimodal condition of haptic/visual (mean 26.95) resulted in the lowest mental demand rankings. Analysis of the contrast between these two conditions revealed that they were not significantly different. In addition, the unimodal conditions of auditory and haptic feedback were also found not to be different from the unimodal condition of visual feedback and the bimodal condition of haptic/visual. As a result, these findings suggest that the unimodal conditions of visual, auditory, and haptic feedback all lead to a low level of perceived mental demand.

Mental Workload – Pupil Diameter

A significant interaction between haptic and visual feedback was found for pupil diameter ($F_{(1,24)} = 6.549$; $p < .05$). Figure 4 shows that the average of the bimodal condition of haptic/visual feedback and the trimodal condition of auditory/haptic/visual feedback resulted in a small pupil diameter (mean 3.556 mm.), thus a low workload.

Further analyses revealed that the trimodal condition of auditory/haptic/visual feedback had a significantly smaller pupil diameter than the bimodal condition of auditory/visual ($T_{(31)} = 2.232$; $p < .05$), and the bimodal condition of auditory/haptic ($T_{(31)} = 2.320$; $p < .05$). These results show the potential trimodal feedback has to reduce workload.

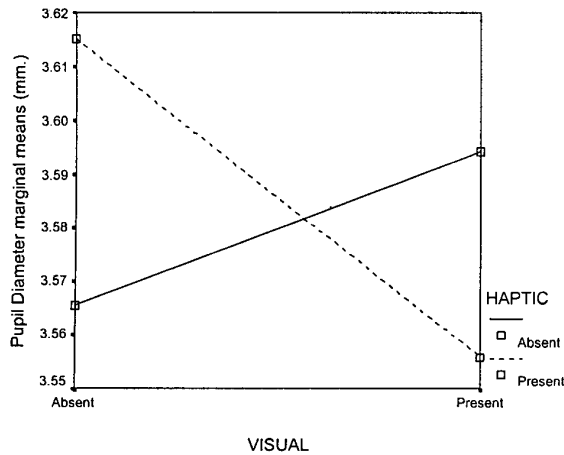


Figure 4. Haptic x Visual interaction for pupil diameter.

Target Highlight Time (THT)

Two significant main effects were found for target highlight time: auditory ($F_{(1,24)} = 15.601$; $p < .05$) and haptic ($F_{(1,24)} = 6.053$; $p < .05$). THT increased when auditory feedback was present and decreased when haptic feedback was present. There was a mean difference of 0.329 seconds between the average of the conditions without auditory feedback (none, haptic, visual, haptic/visual) and the average for the conditions with auditory feedback (auditory, auditory/haptic, auditory / visual, auditory / haptic / visual), shown in Figure 5.

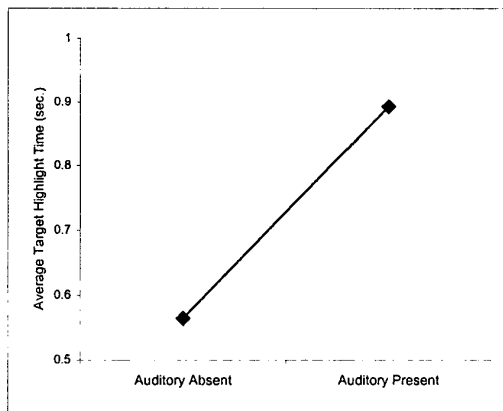


Figure 5. Auditory main effect for THT.

The haptic main effect, in comparison, demonstrated that the average of the conditions without haptic feedback (none, auditory, visual, auditory/visual) had a mean of 0.767 seconds, while the average of the conditions with haptic feedback (haptic, auditory/haptic, haptic/visual, auditory/haptic/visual) had a significantly shorter mean of 0.689 seconds, shown in Figure 6.

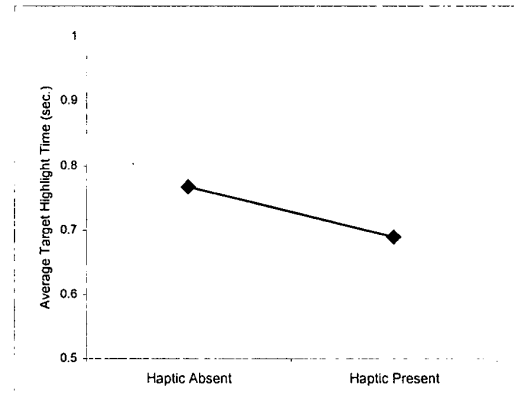


Figure 6. Haptic main effect for THT.

There was a three-way interaction detected between auditory, haptic and visual feedback ($F_{(1,24)} = 4.631$; $p < .05$). The strong influences of the auditory and haptic main effects are particularly evident. To best illustrate this interaction, two two-way interactions are depicted in Figures 7 and 8. Figure 7 depicts the interaction between visual and haptic when auditory feedback is absent. The unimodal condition of haptic feedback (mean .499 s) and the bimodal condition haptic/visual (mean .537 s) provided the two quickest THTs of the eight conditions. Figure 8 depicts the interaction between visual and haptic but this time with auditory present. As shown, the presence of auditory feedback led to an overall increase in THT. The positive influence on performance of haptic and visual feedbacks, seen in Figure 7, was reversed when auditory feedback was added.

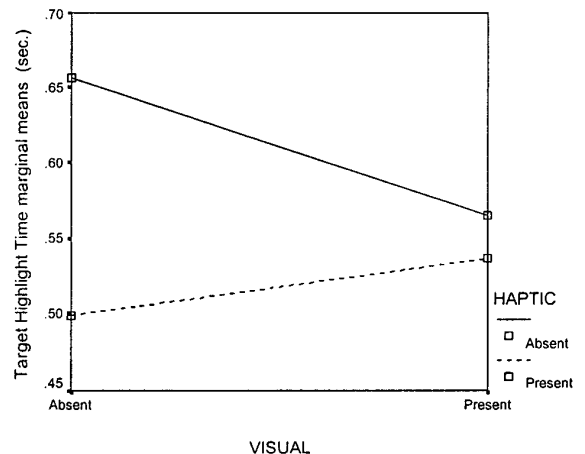


Figure 7. Visual x Haptic interaction when auditory is absent.

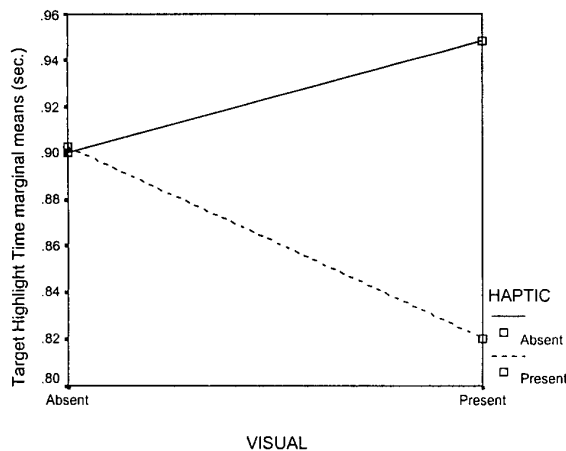


Figure 8. Visual x Haptic interaction when auditory is present.

Overall, all unimodal, bimodal and trimodal conditions with auditory feedback were found to increase THT, whereas haptic and visual feedback alone and in combination were found to decrease THT. This reveals the benefits of incorporating haptic feedback either unimodally or bimodally with visual feedback into interface design.

DISCUSSION AND CONCLUSIONS

The baseline measures of performance of fully sighted users, reported here, mandate the research and development of this same class of interface for individuals with visual impairments. It is essential to determine: (1) how the interaction strategies of individuals with visual impairments differ from the fully sighted population, and (2) are there certain modalities with which there is a significant improvement or degradation in performance? Obtaining these differences and defining critical modality combinations enables movement toward equalizing performance between normally capable users and users with low vision. This study establishes a methodological approach that can be extended to users with visual impairments in order to identify these differences and define critical modality combinations.

Through investigating workload and performance, this research has presented a methodological approach for studying multimodal interfaces, in particular multimodal feedback. The results presented here pertain to how multimodal feedback affected the performance of fully sighted users. However, this same approach can be applied to different populations of users (e.g., users with visual impairments). Analyses of mental workload and performance time revealed several important results that can be applied to the development of multimodal interfaces that would aid fully sighted users now and with additional research, possibility users with visual impairments.

The subjective and objective measures of mental workload yielded several findings. In ranking mental demand, the

unimodal conditions of auditory and haptic feedback were perceived to be as mentally demanding as the unimodal condition of visual feedback, which was perceived to present low mental demand. The bimodal condition of haptic/visual was also found to be as mentally demanding as visual feedback. These findings indicate that alternative modalities such as haptic and auditory offer low mental demand feedback, as perceived by the users. Applying this research methodology to users with visual impairments permits comparisons to be made between populations of users. If these same results were found for users with visual impairments, interfaces offering multiple feedback (auditory, haptic and visual) could allow users with visual impairments to make use of their residual vision while also augmenting communication through their auditory and haptic senses, while maintaining low levels of perceived mental demand.

Analyses of pupil diameter revealed the positive effects of trimodal feedback. When auditory, haptic and visual feedback conditions were presented in combination, the participants' physiological responses indicated reduced workload. This finding was not found for the subjective measure of mental demand, thus underlining the complex nature of workload. Workload can be expressed at many levels, and in this study it was expressed both in terms of perceived demand and physiological response. A disconnect between what users perceive and their physiological responses is common in the human-computer interaction literature. The tradeoff between what users perceive and their physiological responses to workload reveals the potential for trimodal feedback to aid users in reducing mental workload. Again, a comparison needs to be made between what was found in this study for fully sighted users and what would be found for users with visual impairments. Lowering workload from a physiological standpoint, through trimodal feedback, could be extremely beneficial to users with visual impairments. Trimodal feedback not only offers one alternative modality, but two: auditory and haptic feedback. Additional exposure to auditory and haptic feedback may compel users with visual impairments to actually prefer trimodal feedback.

The findings from THT suggest that haptic feedback is beneficial to performance alone and in combination with visual feedback. Conditions that provided haptic feedback were more quickly recognized than conditions that did not provide haptic feedback. The vibration of the haptic feedback was as quickly detected as the highlight of the visual feedback. This is a very important finding, because it suggests haptic feedback is a comparable alternative to visual feedback. In addition, the bimodal condition, haptic/visual, was shown to lead to THTs similar to visual and haptic feedback alone. As with the other results, it is important to determine if these findings hold true for users with visual impairments. If they do, the users with visual

impairments could be greatly assisted by the incorporation of haptic feedback.

Overall these results substantiate the claim that multimodal interfaces, more specifically multimodal feedback, enhance user performance. Figure 9 illustrates the optimal feedback configurations as gauged by the three measures.

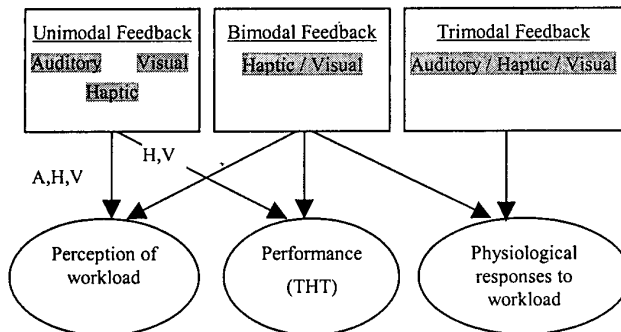


Figure 9. Optimal feedback configurations: gauged by perceptual, performance, and physiological measures.

The methodological approach described here provides a baseline from which to study multimodal feedback. The current results suggest optimal feedback configurations for fully sighted users. They also suggest that multimodal feedback could offer great potential to users with visual impairments. By applying this methodology to a population of users with visual impairments, comparisons and contrasts can be made between populations of users, so that the resulting multimodal interface can enhance the performance of all users.

FUTURE RESEARCH

There are numerous opportunities to apply the described methodological approach for studying multimodal interfaces. The potential of multimodal feedback, presented here, suggests that users of varying abilities can benefit from the augmentation of visual feedback. By examining one user population at a time an extensive knowledgebase can be developed to aid interface designers. Ultimately, the goal is to move towards a universally accessible multimodal interface.

ACKNOWLEDGMENTS

This research was made possible through funding awarded to Julie A. Jacko by the Intel Corporation and the National Science Foundation (BES-9896304) and constituted a portion of Holly S. Vitense's dissertation research.

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