The Effect of Auditory Cues on Haptic-Controlled Excavator Operator Performance

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Abstract

Earth-moving equipment like excavators is difficult to operate. This research aims to investigate the effect of auditory cues on haptic-controlled excavator operator performance. Typically, the human machine interface in excavators relies primarily on visual modality with limited use of auditory which can lead to operator fatigue resulting in errors, lowered efficiency and safety hazard. Recently, there is an effort to introduce haptic modality to excavators. In this preliminary study, we tested the hypothesis that auditory cues will improve the efficiency and effectiveness of the haptic-controlled excavator operator performance. A completely randomized design was used in this experiment with auditory cues being the factor with three levels (no auditory cue, alarm, and voice message). Operator performance was measured by the task completion time, the number of scoops and the number of drops. The Phantom Premium 1.5 haptic device was used to control the excavator simulator in the laboratory. Seven participants completed the experiment. Results indicated that the auditory cues did have an impact on operator performance. Subjective feedback from the participants revealed that most of the participants preferred the auditory cues. Findings from this study can help excavator designers improve their design.

Keywords
Auditory, human-machine interface (HMI), haptic-controlled excavator.

1. Introduction

Traditionally, engineers have designed products centered from a technology perspective. Unfortunately, the technology driven approach has led to information overload and errors causing products to be ineffective [1]. Consequently, operators are usually blamed for 60% to 85% of all accidents [2, 3]. However, accidents/errors are not always the fault of the operator, rather, the design of the product itself [1]. Human factors research has shown that the users’ perspective must be included in the design and development process to achieve effective and efficient results [4]. Human machine interface in many fluid power systems such as human-excavator interface often rely exclusively on visual modality (e.g. levers, pedals) and to a lesser extent auditory modality (e.g. alerts) as the pathway for communicating between the human and machine. However, as operator workload/task becomes heavy, the visual modality becomes overloaded due to the limited number of channels through which the machine and the operator can communicate. The overworking of the visual modality can lead to operator fatigue which ultimately results in under-performance and errors. Excavators are heavy duty fluid powered earth moving equipment used to remove soil from the ground. An example of an excavator is shown in Figure 1. The operation of an excavator requires substantial awareness of the ambient environment. Many of the tasks performed by the operator require extensive use of visual modality which can lead to cognitive overload that can be caused by excessive information exchange, the need to deal with multi-tasking and inadequate workplace infrastructure [5]. Cognitive overload can cause fatigue, poor decision making, errors, and place the operator and excavator surroundings in danger. To avoid cognitive overload, one approach is to improve the richness of the interaction between the operator and the excavator by introducing force feedback or haptics into the interface through which the operator controls and manipulates the excavator. Haptics has great potential if properly integrated into the excavator interface. First, the incorporation of haptics into the user interface of excavator will provide a simultaneous exchange of information between the operator and the excavator, thus, enabling the operator to experience an “immersed” interaction in the environment in which the task is being performed. Thus, in combination with visual display, haptic interface can be used to train operators to better perform digging tasks that require hand-eye coordination, and provide valuable help.
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to novice operators to improve their task performance. Recently, a prototype haptic-controlled excavator has been developed (Figure 1) by introducing ‘haptic feedback’ to the interface design with the expectation that this extra modality will help reduce the load placed on the visual system and lead to improve operator performance. For example, haptic feedback may help alert operator to the presence of buried unusual/unknown obstacles or objects that may be encountered in the work environment, and thus, help the operator avoid them. It is not uncommon to find excavator operators accidentally causing damage to underground utility lines (water, gas, electric power lines etc.) in construction sites primarily due to their inability to see the presence of these lines beforehand. With haptic controlled interface, it is expected that, when the bucket of the excavator encounters such an obstacle, force feedback will be sent to the operator to alerts him/her to the presence of such an obstacle, and enable the operator to perform the task in much more safe and efficient manner. By making use of the haptic control interface instead of the traditional levers and pedals, the excavator operators will be freed from solving the inverse kinematic relationship, and result in a more efficient and effective task performance and shorten training time for novice operators [6].

Since human cognitive processes and perception are built largely upon multimodality, humans have a natural tendency to interact multimodally with the environment. A proper combination of haptic, visual and auditory modalities will result in a flow of information on several parallel channels which has been shown to enhance effectiveness of interaction [7]. While alert is used in excavators, other types of auditory cues might have the potential to ease the visual modality overload. This is especially important to experienced operators who can make decisions with the auditory cues. A well designed multimodal interface for excavators will have the potential to be more intuitive, easy to learn and use, and can reduce operator’s mental workload and stress level resulting in improved situation awareness, better judgment, and decision making.

Some of the recent studies focused on the haptic feedback and the effect of haptic control placement, but in order to achieve the full potential of the haptic-controlled excavators, auditory modality need to be incorporated as well.

Figure1: A prototype haptic controlled excavator
Visual or textual representation to communicate information is of most use when the operator is familiar with the environment and can demonstrate experience and knowledge in that domain [8]. In comparison, more visual and audible representations to communicate information are most effective when the domain area is new and unknown [9]. Most HMI stresses the visual perception, but auditory cues can improve the operators’ understanding of the visual information [10]. Auditory cues are used moderately in many systems to signal an error or the completion of an operation, even though research has shown that operators’ performance improves significantly with additional sound feedback [11]. There are examples in which the use of auditory cues has been very effective. Aviation was one of the early fields to implement auditory warning systems. Research shows that auditory modality has attention capturing features in aviation and improves the overall safety [12]. Alarms in hospitals have improved response time and patient safety [13,14]. Alert signals have allowed automobile drivers to make better informed decisions [15]. Since auditory cues can improve the safety, efficiency and effectiveness of operator performance based on these studies, it is important to investigate it in haptic controlled excavator interfaces. Moreover, with the involvement of both the extremities (legs and hands) in operating levers/pedals, auditory cues are one of the only cognitive resources available beyond visual modality for the haptic-controlled excavator operators.

In this study, a haptic-controlled excavator simulator was used. This simulator allows the operator use the haptic device to control a simulated excavator to perform excavation tasks (Figure 2). It was noted from previous studies using this simulator that many operators had difficulty to use the haptic device to move the excavator to the exact location during excavation task. In this study, we developed three conditions of auditory cues to investigate their impact on operator performance. The first one is without any auditory cue as used before. The second one is to provide an alarm when the boom/bucket assembly is not on the target area (i.e., trench, or a bin). The third condition is to provide a synthetic voice message “on target” when the boom/bucket assembly is on the target and a message “off target” when it is off target. It is hypothesized that auditory cue will have an impact on operator performance. The purpose of this study is to evaluate the effectiveness of various auditory cues on operator performance when operating a haptic-controlled excavator.

2. Method

2.1 Participants
Seven subjects between the ages of 18 and 60 were recruited to participate in the study. Experienced excavator operators were not required for the purpose of this study.

2.2 Simulating Environment and Equipment
The Phantom Premium 1.5 haptic device was used to simulate the excavator controls. The software used to design the simulated excavator environment was coded in C++ and Mat Lab programming and developed by Georgia Institute of Technology. A schematic representation of the equipment setup is shown in Figure 3.
2.3 Experimental Design
A complete randomized design was used to minimize the effect of prior knowledge/experience of the participants. The independent variable was the auditory cues with three levels (no auditory cue, alarm, and voice message). The dependent variable was operator performance measured by the task completion time, the number of scoops and the number of drops.

2.4 Tasks
The participants performed the following tasks under three conditions: no auditory cues, an alarm and voice message.

Task 1: Break through the hard ground and dig a trench at the marked location.
Task 2: Place the dirt in the bins to the right and to the left of the trench until both bins are full.
Task 3: Return to the original position.

These tasks can be accomplished by using the stylus of the haptic device (Phantom Premium 1.5) to control and manipulate the boom/bucket assembly of the simulated excavator. This haptic device has linkages with six degrees of freedom that allow force feedback to the operator (participant). When the bin is full, the content of the bin turns green. During the no auditory cue condition, participants were instructed to perform each task at their own pace. For the other conditions, the participants were instructed to dump the dirt into one of the bins only when the auditory cue was given. They had to repeat the tasks until the bins were completely filled.

2.5 Procedure
Participants were briefed about the experiment and asked to sign an informed consent form to participate in the study. A pre-study questionnaire was administered to each participant to collect demographic information and their experience with computers and the simulation software. To minimize the effect of prior knowledge/experience, all participants underwent a five minute training session to become familiar with the haptic device and simulation prior to testing. Next, a scenario about each task was given to the participants to complete. The order of the experimental conditions (no auditory cue, alarm, and voice) was randomized. Upon completion of the tasks, participants were asked to complete a post-questionnaire about the study. Finally, participants were debriefed and thanked for their participation. The entire experiment lasted about 45 minutes with 5 minute break given between experimental conditions.

2.6 Data Collection
Participant performance data including task completion time, number of scoops and number of drops were automatically captured by the computer.
3. Data Analysis and Results

3.1 Pre-test questionnaire analysis
A five-point Likert scale (1 = Poor, 5 = Excellent) was used to rate the participant skill level of experience with simulation software (e.g. gaming systems). Participants were also asked to rank the frequency of how often they play video games (rarely, sometimes, and very often). The results showed that even though only 35% of the participants play video games sometimes, 47% of the participants rated their skill level at a 4 indicating their confidence using the simulator.

3.2 Descriptive statistics
Performance data of task completion time, number of scoops, and number of drops were used to assess participant performance. Mean and Standard deviation of the performance data were calculated and summarized in Table 1.

<table>
<thead>
<tr>
<th>Experimental Condition</th>
<th>Completion Time (seconds)</th>
<th>Number of Scoops</th>
<th>Number of Drops</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Completion Time (seconds)</td>
<td>Number of Scoops</td>
<td>Number of Drops</td>
</tr>
<tr>
<td></td>
<td>Mean</td>
<td>Standard Deviation</td>
<td>Mean</td>
</tr>
<tr>
<td>No Auditory Cue</td>
<td>426.57</td>
<td>140.94</td>
<td>16.57</td>
</tr>
<tr>
<td>Alarm</td>
<td>360.86</td>
<td>96.83</td>
<td>13.43</td>
</tr>
<tr>
<td>Voice</td>
<td>377</td>
<td>121.74</td>
<td>13.29</td>
</tr>
</tbody>
</table>

Boxplots of the data were constructed and are shown in Figures 4-6.

![Distribution of Time](image-url)
3.3 Inferential statistics
To investigate the impact of auditory cue on operator performance, an analysis of variance was initially considered. Unfortunately, analysis on the residuals revealed violation of normality assumption. Shapiro-Wilk test was used to check the normality of the performance data. Results indicated that the performance data was not normally distributed (W=0.9101, p=0.0552 for Completion time; W=0.9425, p=0.2442 for the number of scoops; W=0.9417,
p=0.2356 for the number of drops) and hence analysis of variance was not appropriate to use. Due to the small sample size, a nonparametric analysis of variance was used to test the hypothesis that the auditory cue has an impact on operator performance. Kruskal-Wallis test was conducted on the performance data.

No statistical significance was found for the completion time ($F_{2,18}=0.5589, p=0.5814$). However, significant difference was found for the number of scoops ($F_{2,18}=10.14, p<0.01$) and number of drops ($F_{2,18}=4.8879, p<0.05$). For significant results, pairwise comparison was done using the Dwass, Steel, Critchlow-Fligner multiple comparison procedure. For the number of scoops, a significant difference was found between no auditory cue and alarm (Wilcoxon $z=2.9471, p<0.01$), no auditory cue and voice message (Wilcoxon $z=2.5280, p<0.05$). For the number of drops, a significant difference was found between no auditory cue and voice message (Wilcoxon $z=2.5975, p<0.05$).

3.4 Post-test questionnaire analysis
The participants were asked about their experience with the simulator. 86% of the participants preferred the auditory cue and 57% of them preferred the voice message specifically. In addition, 43% of the participants also expressed lack of comfort operating the haptic device since no arm rest was provided.

4. Discussion and Conclusion
The most salient finding of this research is that auditory cue had a significant impact on operator performance of a haptic-controlled excavator simulator. It indicates auditory modality needs to be better utilized in the haptic-controlled excavator.

Participant performance data as measured by the number of scoops and the number of drops revealed that having auditory cue helped participants completing their tasks. Feedback from the post-test questionnaire confirmed this since majority participants (86%) acknowledged that auditory cues helped. Some comments mentioned that with auditory cues, they had easier time operating the haptic device. This could be seen from their performance of more number of scoops and less number of drops. Contrary to these two performance measures, no significant difference in task completion time was found among the three conditions. This surprising result might be explained by the instructions given to the participants. Participants were instructed to wait till they heard the auditory cues before taking the next action for the alarm and voice message conditions. However, participants did not have any constraint and were self-paced when no auditory cue was present. Another surprising finding was the lack of significant difference between the two auditory cues: alarm and voice message. Only slightly more participant preferred voice message to alarm. Since this experiment was conducted in a laboratory environment and in a much simpler way than the actual field, the difference between the two auditory cues might not play a big role in participant performance.

Although statistical difference was found on performance data, it needs to point out there is large variability among the data. In addition, only seven participants completed the experiment. The small sample size contributed to the heterogeneity and lack of normality and was the reason no parametric approach was used to analyze the data in this study. Therefore, readers are advised to interpret the findings of this study with caution.

Haptic controlled excavators have the potential to make this traditionally highly skilled occupation more accessible to more people including women. However, it is still in the early stage of the development. One area for improvement is the use of auditory cues. This preliminary study indicated proper use of auditory cues might help improve operator performance. Although the results are encouraging, more work needs to be done. In the future, large samples will be used and more realistic settings will be used in the experiment.

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References