Designing a Multimodal Warning Display for an Industrial Control Room

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ABSTRACT

This paper presents the development of a multimodal warning display for a paper mill control room. In previous work, an informative auditory display for control room warnings was proposed. The proposed auditory solution conveys information about urgent events by using a combination of auditory icons and tonal components. The main aim of the present study was to investigate if a complementary visual display could increase the effectiveness and acceptance of the existing auditory solution. The visual display was designed in a user-driven design process with operators. An evaluation was conducted both before and after the implementation. Subjective ratings showed that operators found it easier to identify the alarming section using the multimodal display. These results can be useful for any designer intending to implement a multimodal display for warnings in an industrial context.

CCS CONCEPTS

• Human Centered Computing → Sound-based input / output

KEYWORDS

Warnings, alarms, multimodal interaction, auditory display, process industry

ACM Reference format:

J. Fagerlönn, K. Hammarberg, S. Lindberg, A. Sirkka, and S. Larsson. 2017. Designing a Multimodal Warning Display for an Industrial Control Room. In *Proceedings of AM '17, London, United Kingdom, August 23–26, 2017*, 5 pages. <https://doi.org/10.1145/3123514.3123516>

INTRODUCTION

Poor alarm management and poorly designed warning sounds are common problems in industrial control room contexts [1]. The urgency mapping between the sounds and the urgent events is often inadequate [1], which can make the sounds confusing. Furthermore, common abstract tonal warnings can be challenging to learn and interpret, causing a decrease in operator performance and increased levels of cognitive load. In a bid to overcome the issues with auditory cues, a new type of auditory warning display has been proposed [2]. The display contains spatially presented informative sounds (auditory icons), which are presented with brief tonal sounds that contain urgency information. The auditory display was designed with control room operators and has been evaluated in a long-term study in a paper mill control room. The results showed a significant improvement in terms of operators' ability to identify the source of the danger. Furthermore,

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AM '17, August 23–26, 2017, London, United Kingdom
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<https://doi.org/10.1145/3123514.3123516>

the overall auditory environment was improved, which may have a positive effect on operators' well-being.

Auditory cues can effectively catch and guide the attention of users, regardless of their visual focus. Furthermore, using sound that can easily be associated with the alarming event can be an effective way to convey urgent information [3–5]. Moreover, previous research has shown that the perceived urgency of the warning can be systematically changed by manipulating both spectral and temporal parameters [6–8], helping the user to prioritize incoming information.

However, one potential issue with pure auditory solutions is that the displayed information is lost if not repeated. Visual cues, on the other hand, can persist over time and offer even greater spatial accuracy. Additionally, auditory masking and hearing impairments among users may increase the risk that important information is lost. Thus, using a combination of visual and auditory cues for warnings may be beneficial. If well designed, the combined auditory and visual display may increase operator performance. On the other hand, if the information in the two sensory channels is not designed with consideration for each other, the information may become contradictory rather than complementary. Furthermore, there is always a risk of adding yet another information system, making the control room environment more cluttered and challenging to handle than it already is.

1.1 Aim

The aim of the present work was to develop a new type of multimodal display to enhance the effectiveness and acceptance of warnings in an industrial control room. The present paper focuses on one of the control rooms that already have the auditory display reported above and in [2]. The main idea was to create one multimodal system where all information, whether auditory or visual, is integrated and optimized for human reception. The display was evaluated with operators in a long-term study.

2 METHOD

2.1 The control room setting

The target control room (Fig. 1) is located in a paper mill in Sweden. Operators work in six-hour shifts in teams of three to four operators. Their main task is to monitor visual displays that show the production flow in the production sections. Operators are notified on the screens, as well as by auditory warnings, if action is needed. The control room is equipped with the auditory display designed and evaluated in previous work [2]. The auditory system has been implemented for several years; thus, most operators should be very accustomed to its sounds.

Figure 1: The control room.

2.2 Auditory display design

Fig. 2 shows an overview of the control room and speaker placements.

Figure 2: Speaker placements in the control room.

The warning sounds are played using a four-channel audio system. The speakers are positioned so the warning sounds are played in directions from relevant production sections, i.e., the part of the control room wherein operators solve the problem causing the warning. The operators are required to respond to alarms during breaks. Thus, one speaker is positioned in the operators' lunchroom. The features of the warning sounds are presented in Table 1.

Table 1: Characteristics of the warning sounds.

Section	Urgency level	Notes	Auditory icon
wood chipping	very low	-	breaking twig
wood chipping	low	A3	breaking twig
wood chipping	medium	A3-E4	breaking twig
wood chipping	high	A3-E4-E4	breaking twig
washing	high	C4-F4-G4	water drop
cooking	high	A4-E4-E4	kettle steam hiss

The auditory display contains a set of warnings used to represent urgent events in three operating sections. The sounds are based on a design principle in which each warning sound consists of two parts (played in a sequence). One part (tonal component) conveys urgency information, while the other part (auditory icon) conveys information about the relevant section. Furthermore, the sounds are repeated according to specific intervals. More detailed information about sounds and the repetition intervals was presented in the previous study [2].

2.3 Visual display design

The visual solutions were designed in close collaboration with the users of the specific control room environment. First, a workshop was conducted with operators to establish current problems and a vision for future development. After that, prototypes and mock-ups were developed, tested, and refined with operators in an iterative design process.

The developed solution (evaluated in the present study) consists of three types of visual units. The first type (see Fig. 3) consists of several small “light jars.” The main purpose of these units is to direct the operators’ attention to a specific area of the control room by flashing in time to the alarm sound. In addition, they are color coded to different operating sections. The idea is to draw the operator’s attention to specific computer monitors, but in a subtle manner. The signals are designed to be discreet and pleasant, but still easily caught in the corner of the eye.

Figure 3: Lights indicating an active warning.

The second type of unit (see Fig. 4) is a panel that gives an overview of active warnings. Osvalder et al. [9] describes the operator’s need for the perception of a system’s status when entering the room or looking up from a secondary task. The panel is designed to provide subtle but unmistakable information about which operating section has active warnings. The design avoids traditional sirens and direct lighting. Instead, the panel is designed in plexiglass, and the sources of light are not visible to the operators.

Figure 4: Warning overview display in the ceiling.

The third type of unit (Fig. 5) was developed for the coffee/lunch area of the control room used by operators during breaks, etc.

Figure 5: Warning overview display in lunchroom.

In addition to giving clear warnings and information, this unit was designed to be an aesthetically pleasing contribution to the room. Like the second unit type, this unit type gives an overview of active warnings. The graphical symbols were designed to correspond to the icons of the auditory display.

2.4 Procedure

The evaluation consisted of two collections of data. Before the implementation of the visual displays, a questionnaire was sent to the operators. The questionnaire contained questions and statements regarding the effectiveness and appropriateness of the warning system. The questionnaire was written in Swedish. Operator acceptance was assessed using the acceptance scale proposed by Van der Laan, Heino, and de Waard [10]. According to the method, participants are asked to rate the perceived usefulness of the sounds on five-point scales ranging from useless to useful, bad to good, superfluous to effective, worthless to helpful, and sleep-inducing to alertness-raising. Similarly, the perceived satisfaction of the sounds is rated using scales ranging from unpleasant to pleasant, irritating to likeable, annoying to nice, and undesirable to desirable.

The second data collection was conducted around six months after the implementation of the visual displays. The second questionnaire contained similar questions and statements to the first data collection. However, questions were also asked regarding the visual solution and the total multimodal warning solution, rather than the auditory solution only.

2.5 Participants

In total, 28 operators participated in the first data collection. However, 10 operators did not participate in both of the study's collections of data, and one subject was

discarded due to contradictory personal data (between questionnaires), leaving 17 operators (three females and 14 males) for the final data analysis. The mean age for the 17 operators was 47 years ($SD = 11$) at the time of the second data collection.

3 RESULTS

Fig. 6 shows the difference in perceived acceptance between the auditory display and the multimodal display. Incomplete data from one subject were discarded ($n=16$). According to the method of Van der Laan, Heino, and De Waard [10], results are summarized into the two factors of “usefulness” and “satisfaction.” The multimodal display resulted in a slightly higher mean score compared to the auditory display, both in terms of usefulness (an increase from 0.7 to 1.1) and satisfaction (increased from 0.5 to 0.9).

Figure 6: Rated acceptance for the auditory display and the multimodal display. X-axis represents “usefulness” and Y-axis represents “satisfaction”.

The operators rated the multimodal display considerably more helpful for identifying the alarming section. The statement in the questionnaire was “It is easy to identify the alarming section” and the scale ranged between 1 (not at all agree) and 7 (totally agree). The mean rating increased from 4.6 ($SD = 1.1$) to 5.6 ($SD = 1.2$). A correlated samples t-test revealed that the difference was significant ($p < 0.02$). Furthermore, the operators rated the visual elements helpful when solving problems. The statement was “The visual signals help me solve the problems effectively” and the mean rating was 5.2 ($SD = 1.5$) on a scale from 1 (not at all agree) and 7 (totally agree).

4 DISCUSSION

The focus of the present work was to develop a new type of multimodal display to enhance the effectiveness and acceptance of warnings in a paper mill control room.

The conducted work was based on an already designed and implemented auditory display. The main aim was to investigate if complementary visual displays would increase the effectiveness and acceptance of the solution.

In terms of acceptance, the multimodal concept received higher ratings, both regarding usefulness and satisfaction. The relatively small differences indicate that the additional visual components had a limited positive effect on acceptance.

Ratings also showed that it was significantly easier to identify the alarming section with the multimodal display. Moreover, the operators rated the additional visual displays as helpful during problem solving. It should be noted that the operators had proper time to learn the auditory signals prior to the start of the present evaluation. Furthermore, the operators evaluated the multimodal concept over a relatively long time period (around six months). Thus, the results strongly indicate that the addition of visual displays may be a beneficial complement when using informative auditory displays in control room settings. While the sounds catch and guide the operators to the relevant control section, the visual displays can hold information over time and provide an overview of the alarm situation, including more precise spatial information.

Most importantly, the results provided in the present and previous study [2] give an example of how control room warnings and alarms can be improved with adequate auditory and visual signals. Several studies have shown that auditory icons (meaningful non-speech sounds) can be appropriate warnings in various contexts. The present long-term tests strongly indicate the appropriateness of informative non-speech sounds. Even though the specific design solutions may only be useful in the present control room, the design principle may be utilized in other industrial contexts.

The visual displays evaluated in the present study consist of prototypes. They may be further developed in future research and development. For instance, the visual displays do not convey any urgency information. Future research should investigate if presenting urgency information using the visual displays can be beneficial in the proposed type of multimodal warning display.

Additionally, the present study focused on subjective ratings of the warnings; no objective performance measures were assessed. It would be interesting to investigate performance aspects, such as the time to find and/or solve problems.

The multimodal display was designed in a user-driven process involving operators of the control room. The user involvement may have contributed to more positive scores in various ways. First, since the operators know what works well for them, the participation may have contributed to generating more appropriate auditory and

visual cues. Second, participation may have made the operators rate the designed solutions more positively. The present evaluation was not focused on studying effects of participation on subjective ratings, but such complementary investigation would be interesting. In a parallel study (not yet published), however, the operators will judge a multimodal solution after significantly less user involvement.

Finally, the work presented in this short paper is ongoing. Further analyses of quantitative and qualitative data will be conducted during the spring of 2017. In addition, a similar multimodal display has been designed and implemented in another control room. Combining the results from both studies may bring an even better understanding of the appropriateness of the proposed design.

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