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# The warning glove – Development and evaluation of a multimodal action-specific warning prototype

Ulrike Schmuntzsch*, Christine Sturm, Matthias Roetting

*Technische Universität Berlin, Department of Psychology and Ergonomics, Chair of Human-Machine Systems, Marchstr. 23, Office MAR 3-1, 10587 Berlin, Germany*

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ABSTRACT

This paper has two objectives: first, to introduce the *concept of multimodal action-specific warnings* and its prototypic realization in the form of a warning glove and second, to present the main findings of a user study that was conducted to test the warning glove against a conventional warning system. Regarding the first goal, the combination of *multimodality* and *action-specificity* was implemented by attaching electronic actuators on a right-handed glove for transmitting visual, auditory and tactile feedback. For the second objective, a user study was conducted to test the hypothesis that the warning glove is capable of obtaining faster responses and to determine the perceptions of the users regarding the appropriateness of the warning glove. The results confirmed the assumption of faster response times and participants perceived the warning glove to be 'fairly appropriate'. These results warrant further development of this multimodal action-specific warning glove.

## 1. Introduction

Industrial companies are nowadays confronted with increasing global competition. In order to keep up with this trend, progressive specialization and customization of products and services is underway. This so-called third industrial revolution particularly affects the human–machine interaction in the manufacturing industry (Spath et al., 2012). Within the emerging Industrial Product-Service Systems (IPS$^2$) the supplier guarantees functionality of machine tools, availability of production equipment or manufactured results rather than just selling machines (Meier and Völker, 2008). In case of system malfunctions, warranty obligations necessitate rapid re-establishment of a fully operational system, e.g. with the help of maintenance. Following Reason (1997) and Lind (2008), maintenance includes activities such as unscheduled repairs, planned preventive operations and inspections as well as calibration and testing.

Performing maintenance in industrial facilities has always been complicated and prone to error. In an era of increasing specialization and customization of technical tools and machines, combined with the pressures of time and productivity, maintenance is a real challenge and a source for potential error (Dhillon, 2009). Reason and Hobbs (2003) evaluated the proportion of human performance problems relative to the total amount of operations. Even in a high-risk technology like nuclear power plants, they reported a great variance in human errors which occur during different kinds of activities:

- 42–65% during maintenance, calibration and testing activities
- 8–30% during normal plant operations
- 1–8% during abnormal and emergency cases.

These figures show how maintenance-related problems make up a particularly high proportion of errors and Dhillon (2009) even claims this percentage will increase. According to Reason and Hobbs (2003), most of these maintenance errors are associated with installation and reassembly. Based on Rasmussen's classification of errors (1982), Reason and Hobbs (2003) further distinguished between different causes of error such as "memory lapses", "knowledge errors" as well as "recognition failures", "slips" and "rule errors". Focusing on error prevention, especially the latter three, would be significant since they cause about 53.5% of worker safety incidents and 34% of product quality incidents (Reason and Hobbs, 2003).

In complex industrial facilities it is unrealistic to design out or to guard against all hazards (Sanders and McCormick, 1993). Therefore, error prevention also means providing human operators with the best possible assistance, including warnings.

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* Corresponding author. Tel.: +49 (0)30 314 73820.
*E-mail address:* ulrike.schmuntzsch@mms.tu-berlin.de (U. Schmuntzsch).

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Warnings are defined as safety communication which provides information about hazards. They aim at avoiding or at least minimizing undesirable consequences (Wogalter et al., 2012). There are many different kinds of warnings, especially in complex industrial facilities. Commonly, a warning serves four purposes: first, to communicate important safety information; second, to ensure safer behavior, third, to prevent incidents causing personal injury or property damage and fourth, to help people remember information previously learned. To provide proper warnings it is important to know what, whom, when and where to warn (Wogalter et al., 2012). This implies that the person addressed in a certain situation should be able to notice the warning, understand it and transform it into a proper action, which means into safety behavior. To adequately implement these issues it is necessary to focus on optimizing the perceptibility of the warning signal and to provide a direct linkage between the error and the human operator's action. When warning signals are carefully designed in accordance with these guidelines, they can function as an effective prevention measure for improving occupational safety.

## 2. Theoretical background

A good deal of research has been conducted to explore the nature and effectiveness of warning systems and to develop proper guidelines for their design, inter alia from Lehto and Miller (1986), Edworthy and Adams (1996), Laughery and Wogalter (1997), Wogalter et al. (2001), Wogalter and Conzola (2002), Smith-Jackson and Wogalter (2004) or Wogalter and Mayhorn (2006).

The most influential theories forming the theoretical background of warning systems are the communication theory by Watzlawick et al. (1967) and the human information processing model by Wickens and Hollands (2000). Since both theories are important to understanding the functioning of warnings and their design, Wogalter et al. (1999) and Wogalter (2006) combined them in the C-HIP model, an integrated theoretical framework for warnings. According to this framework, warnings first have to be noticed and encoded, which means attracting attention. Secondly, warnings have to provide understandable and persuasive information about the hazard, its consequences and instructions on how to avert the danger (Laughery, 2006). Regarding the first step, the channel (i.e. medium and modality) for transmitting the warning plays an important role. Accordingly, both medium, which contains the information, and modality, which appeals to different kinds of human senses, determine how well and fast a warning will be perceived (Laughery, 2006; Wogalter et al., 2012). As to the modality, more salient signals like sounds are likely to attract more attention than visual signals (Stanton, 1994). Hence, a modality that functions well is an essential precondition for immediate and proper responses to warnings. Table 1 gives an overview of the human senses that are usually targeted in warning design and their respective perception thresholds, neuronal processing times and response times.

To accelerate detection and identification, several studies recommend using multimodality. Accordingly, study results from Oviatt et al. (1999) and Oviatt (2003) substantiate the superiority of multimodal over uni-modal interfaces with respect to error prevention and correction. Furthermore, Hecht et al. (2005) found that mean response times ranged from 318 to 430 ms for uni-modal stimuli, whereas for bi-modal stimuli mean response times ranged from 272 to 302 ms and tri-modal produced mean response times of 263 ms.

Another important factor in increasing the detection and identification of warnings is their placement (Frantz and Rhoades, 1993; Wogalter and Silver, 1995). For a more rapid alert, warnings should be located in close proximity to the potential hazard. In this regard, the haptic senses, which can be divided into tactile and kinesthetic, become increasingly important. The kinesthetic perception is perceived by internal receptors for movement, position and force. In contrast, the tactile senses are receptors in the upper skin layers for pressure, vibration and temperature (Goldstein, 2008).

**Table 1**
Perception thresholds, neuronal processing times and response times for visual, auditory and tactile stimuli.

| Senses | Perception thresholds | Neuronal processing times | Response times |
|---|---|---|---|
| Visual | 400–700 nm (Goldstein, 2008) | 50 ms (Macefield et al., 1989)<br>20–40 ms (Marshall et al., 1943) | 150 ms (Boff and Lincoln, 1988)<br>190 ms (Brebner and Welford, 1980) |
| Auditory | 20 to 16,000 Hz<br>highest sensitivity 2000 to 5000 Hz (Schmidt and Schaible, 2006) | 8–10 ms (Kemp, 1973)<br>10 ms (Macefield et al., 1989) | 110–120 ms (Boff and Lincoln, 1988)<br>160 ms (Brebner and Welford, 1980) |
| Tactile | 10–500 Hz for vibration (Goldstein, 2008) | ~2 ms, when the stimulus is presented on the head<br>~20 ms, when stimulus is presented on the hand<br>~30 ms, when the stimulus is presented on the foot of a person 1.7 m tall (Macefield et al., 1989) | 110–120 ms (Boff and Lincoln, 1988) |

Several applications in the emerging area of smart clothing and wearable computing technologies have demonstrated how different output devices using vibration and force are directly connected to the human body in order to guide, alert or correct the user (Cho et al., 2009). Some examples include a haptic shoe for the visually impaired to guide their way and to warn against obstacles (Saha, 2012), a uniform for firefighters, which visually indicates danger coming from heat (Gearfuse Online Magazine, 2008), a vibrotactile feedback suit that improves human motor learning (Lieberman and Breazeal, 2007) or an intelligent curve warning system for motorcyclists in the form of a tactile warning glove (Huth and Biral, 2012). However, these applications use only one modality and therefore do not utilize the advantages of multimodality.

These theories, studies and applications lead to the assumption that the combination of *multimodality* and *action-specific placement* could be a promising approach to increase detection and identification of warnings. This idea constitutes the basis for the *concept of multimodal action-specific warnings* and its prototypic implementation presented below.

## 3. The concept of multimodal action-specific warnings and its prototypic implementation

### 3.1. *The concept of multimodal action-specific warnings and its underlying ideas*

Conventional warning systems in industrial facilities are usually designed to be multimodal and located directly on the machine. Primarily sounds are used to attract attention, while visual notifications offer additional information (Wogalter et al., 2012). It is crucial to consider two characteristics of these systems. Firstly, only two of the three most important human senses are utilized, excluding the haptic ones, although these senses stimulate equally fast responses as the auditory and even faster responses than the visual (Boff and Lincoln, 1988). Secondly, the action-specific