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Providing cognitive support with technology-based warning systems

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New and emerging technologies promise to revolutionize risk communication. The benefits of technology are discussed with regard to the components of a recently described warning process model. Examples are provided to illustrate how technology can potentially improve information accessibility and cognitive support. Design principles such as warning interactivity, dynamic modification and personalization are considered as potential applications of technology that should enhance warning effectiveness in future technology-based systems.

Keywords: Warnings; Cognitive-support; Technology; Sensors; Hazard-avoidance.

1. Introduction

The main purpose of warnings is to decrease harm from hazards to people and property. Typically, one thinks of warnings as labels, stickers or signs. Common examples include labels located on cigarette packages and air bag stickers on sun visors. In the future, many traditional static-display methods will likely become more dynamic. Future warning systems will likely have properties that are different and better than those inherent in traditional static warnings. Developments in technology such as in flat panel displays could provide dynamic warnings in applications heretofore not considered. Computers and sensors can be used to process information to enable warnings to be appropriately tailored to the situation and characteristics of the target user. While technology-based warning systems such as smoke detectors have been in widespread use for years, the advent of new and emerging technologies promises to extend current applications and revolutionize risk communication by disseminating and managing safety information in electronic form. This article describes how existing and future technology can be applied to warnings and risk communication to improve information accessibility

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and provide cognitive support. Here, cognitive support refers to the assistive aspects of technology that enhance the mental capabilities (and avoid the limitations) of users.

2. Warning process model

To demonstrate how technology-based warning systems might contribute to user safety, the benefits of technology adoption will be discussed in the context of a basic warning process model described by Rogers *et al.* (2000). In this model, a user's interaction with a warning involves four broad components: notice; encode; comprehend; and comply. Specific examples are provided to illustrate how technology might be implemented into warning design and application at each level of the Rogers *et al.* (2000) framework. It is recognized, of course, that other models could have been used (e.g. Lehto and Miller 1986, Edworthy and Adams 1996, Wogalter *et al.* 1999). Moreover, the recommendations could have been outlined without the use of such a model. For another review of warning technology that is not organized around a stage-model, see Wogalter and Conzola (2002).

This review is focused on visual and auditory warnings, since the use of the 'other' senses (i.e. smell, taste and touch) in warning is relatively rare. However, there are numerous examples of warnings that have been designed to accommodate these senses, including the following: (1) an extremely bitter taste added to detergents makes the taste so repulsive that children, who might otherwise drink it, spit out the solution; (2) an odour added to natural gas piped to the home aids homeowners to detect gas leaks; and (3) an aircraft is equipped with a control stick that shakes when the plane is being manoeuvred with too high a slope indicative that a different control movement is necessary to reduce the slope. These are just a few interesting examples of how the 'other' senses can be used to transmit information. It is to be hoped that there will be more of these instances of warnings designed to accommodate the 'other' senses to cover in future reviews.

3. Notice

According to the Rogers *et al.* (2000) model, a warning must first be noticed to be effective. This first stage of the Rogers' model is similar to Wogalter and Leonard's (1999) attention capture or switch stage. For both models, it is critical (at this stage) that the warning draws sufficient attention to itself to enable the process to move on to subsequent stages of the model.

Depending on the task, context, or environment, warning noticeability can be enhanced by the use of a variety of physical design characteristics, including adding a distinctive colour or a pictorial symbol, using a larger font or increasing the contrast between the warning message and its surroundings. For example, warnings printed in a colour distinctively different from their surroundings are noticed more quickly than those printed in the same colour as other surrounding material (Laughery *et al.* 1993). Yet colour and most other physical design factors of traditional printed warning labels are passive (i.e. static). A relatively simple technological enhancement designed to increase noticeability is to illuminate a warning when someone enters a hazardous part of the environment. Doing so serves the role of focusing people's attention on the warning at the appropriate time (when a person and the hazard are present). It also provides stimulus change.

Why is stimulus change important for warnings? In some contexts, an unchanging stimulus can produce habituation, which means that the stimulus is becoming increasingly less effective at attracting people's attention. Furthermore, when an individual is exposed to the same stimulus repeatedly over time, less attention is given to that stimulus during subsequent exposures. Therefore, stimulus change plays an important role in slowing the habituation process in some conditions.

Consider a road sign stating: 'Bridge ices before road.' The warning message concerning icy roads is conditional and pertinent only during cold weather. The 'Bridge ices' sign is often permanently erected and visible during summer months when freezing is not a concern. As a result, it is appropriate to ignore the sign when conditions are not relevant. This becomes a problem when people do not recognize that the weather conditions make the sign relevant. A potential solution is to use temperature detectors so that presentation of the icy bridge sign is limited only to cold weather. Likewise, the noticeability of a school zone signs are, in some locales, enhanced by having them flash only during the times children go to or leave school. Of course some signs are nearly always relevant, such as 'Stop' signs.

Clearly, one of technology's main benefits to facilitating warning noticeability is that it can effectively offset habituation associated with static warnings by incorporating stimulus change into the design of warnings. The use of sensors would also act to reduce the ambiguity of hazardous situations such that people will notice when they need to heed warning information. Presentation when and where the warning is needed will reduce the likelihood that people will miss seeing a warning. Also, false alarms are likely to be reduced. Of course, stimulus change needs to be sufficiently large in a perceptual sense to benefit noticing and limit habituation.

There are (at least) two ways in which technology can be used to increase the noticeability of warnings. The first is to design the system to detect – or notice – the hazard or at least a surrogate of the hazard. A second way is to develop cognitive prosthetics that aid the user or receiver in noticing the warning. These possibilities are discussed in more detail in the sections that follow.

3.1. Placing the burden of 'noticing' on the system

Advanced warning systems are likely to incorporate sensors capable of detecting hazardous conditions. Currently, there are already numerous detection systems available that can 'sense' motion, heat and weight. These sensors provide input into systems that could, in turn, provide a warning. They could be used to detect persons (or other things) entering a restricted environment or doing some other potentially hazardous activity. For example, drivers are warned by simple sensor-based systems in vehicles that their door is not fully closed or that they are not wearing seatbelts. In one empirical demonstration, Wogalter *et al*. (1993) used an infrared photoelectric detection system as a sensor to initiate a warning presentation when individuals entered a designated risk area. Here a voiced presentation of the warning information benefited compliance performance compared to no voice presentation.

The kinds of hazardous conditions that could potentially be detected by sensor devices are quite varied. For example, sensors in some cars detect the presence of a small child positioned in the front seat. A motion sensor in a hospital room could alert nurses when a patient is not in bed. At some locations, simple sensor systems detect the height of vehicles too tall for a bridge underpass.

The sensors do not necessarily have to detect a person or thing, but could detect correlated indications of the presence of a person or thing (see also Wogalter and Dingus 1999). For example, sensors in passenger vehicles could detect the presence of an infant/

child booster seat in the front seat rather than the actual presence of the child. Configurations of different types of sensors could detect more specific indications of hazards. For example, the combination of a weight and motion detector is likely to provide a more accurate assessment that a small child is in the front seat and not a package of goods (and thus could display a warning in the former and not in the latter). Some automotive systems include proximity sensors that alert drivers when another vehicle is dangerously close. Furthermore, navigation systems with global positioning systems can be used to display warning information about known hazards within specific coordinates.

Sensor devices can also be used to detect hazards that would not otherwise be perceived. One currently available example is a carbon monoxide (CO) detector. This device 'senses' the presence of poisonous CO gas that can be neither smelled nor seen. Another currently available example is tags or clothing sensitive to poisonous vapours and/or radiation (e.g. Walsh *et al*. 1999). The colour of the material changes to indicate the presence of hazardous radiation. In these instances, technology serves as a proxy for the sensory organs, thereby allowing the detection of hazards that would not otherwise be detected. The burden of 'noticing' the hazard is placed on the system and, to a lesser extent, the user, although, of course, the user must be able to detect the warning display when it is given.

3.2. Enhancing the display

Technology can enhance the ability of warning displays to attract people's attention in a number of ways, such as using colour, increasing its size and adding pictorial symbols. These and other display features that facilitate warning noticeability are described in Wogalter and Leonard (1999). With greater use of technology, such as when connected to a computer with the appropriate programming, warning displays can be more dynamic and targeted to the particular user. For example, if a user is red – green colour blind or has auditory insensitivity at certain frequencies, the sensory characteristics could be modified to give a compensatory presentation in a different modality. Sophisticated systems could also customize the presentation to the needs of specific users (Essa 1999, Kwahk *et al*. 2002), such as giving an alert that a particular blood pressure medicine was not taken at the scheduled time.

Auditory warnings are particularly useful in situations in which a person's attention is focused on a visual task. Technology-enhanced displays might also incorporate the use of digitized voice systems. Consumer products, such as answering machines and greeting cards, already make use of inexpensive miniaturized voice production units. Similarly, digital recording and presentation technology could be employed to present noticeable voice warnings, such as when a visual warning might be missed or when visual presentation could interfere with performance of a (visual) task.

4. Encode

Once the warning is noticed, processing may continue so that warning information is translated and stored as an internal mental representation. Extensive literature in cognitive psychology concerning learning, memory and other cognitive processes describes numerous factors that benefit the encoding of information. For example, one well-studied method shows that spaced presentation of to-be-learned information (distributed across different points in time) yields better encoding (and subsequent performance) than massed presentation ('cramming') while holding total presentation time constant (Underwood 1961). Thus, in some cases, important safety-related information could be learned more efficiently through the use of technology-based systems that present the to-be-learned information via shorter presentations distributed across time rather than ones that present the information all at once.

Technology-based warning systems offer improved information accessibility because they can deliver information at the points of time when it is needed. For example, Internet-based devices could deliver risk-related information only when specific (hazardous) tasks are performed. Using a walk-up touch screen display connected to the Internet or a local intranet, a worker could access material safety data sheets for the chemicals he/she is handling. Wireless handheld (e.g. personal digital assistants (PDAs)) or other display units (e.g. cellular telephones, electronic tags) could present information so that it is delivered when and where the information is needed (Frantz and Rhoades 1993, Wogalter *et al.* 1995).

For the presentation of more complex information, technology could provide cognitive support by presenting the tasks in a step-by-step format. One way in which this could be accomplished is through the use of technology such as the 'talking box' used in a study conducted by Conzola and Wogalter (1999). When participants opened the box, a miniaturized voice system delivered a sequence of precautionary steps that were supposed to be performed before installing a computer disk drive in the box.

When safety instructions require numerous complex steps, working memory can often be overloaded if the sequence is provided in one continuous presentation. In these situations, similar to the distributed presentation strategy described earlier, technology could be arranged to give carefully timed or user-prompted instructions to reduce the likelihood of overloading the cognitive system. More sophisticated systems could be designed to present the next instruction only when it detects that the previous step was successfully completed. Systems could also match presentations with other user characteristics, including their cognitive capabilities and limitations. For example, simply presenting the information at a slower rate and limiting the delivery of new concepts could significantly reduce the demands placed on an older adult's working memory capacity. In addition, experienced and knowledgeable users who already know the material might be presented with only the content necessary to prompt and remind them of the safety precautions needed in the situation.

5. Comprehend

Although users may notice and encode the words or graphics of a warning display, they still may not understand the intended message. In other words, it is possible for a person to understand each of the individual words of a warning or see all the parts of a symbol, yet not comprehend the entire intended meaning. Consider the warning statement: 'Contains Carbon Monoxide'. This statement would not be an effective warning if the reader does not know that this gas is poisonous. Hopefully, almost no one thinks CO is beneficial or non-toxic. But for any people who do, the consequences could be disastrous. Generally, it is better to have no understanding of a warning thst leads to benign effects or consequences than it is to have it create a misunderstanding or confusion that results in personal injury or property damage. For example, in the USA medications have a warning that displays a symbol of a pregnant woman together with a slash prohibition symbol. This symbol was intended to indicate that pregnant women should not take this drug. If this symbol were misinterpreted as an illustration for birth control, the consequences could be disastrous. Clearly, correct comprehension of warnings is important.

5.1. Receiving more information

Warnings generated electronically can permit the presentation of more detailed information beyond a warning initially displayed. As with links in hypertext or on Internet pages, users could call up richer descriptions of related warning information. Research indicates that more explicit warnings that provide detailed, specific information concerning hazard avoidance are more effective at reducing the likelihood of injury than less explicit warnings (e.g. Laughery and Stanush 1989). A brief warning could be expanded with further, more specific information through links.

Other examples of technology-based warnings benefiting comprehension include electronic display boards erected on busy, urban highways. These massive changeable signs are erected for the purpose of alerting drivers some distance away of the road conditions ahead. They can do more than simply report on existing conditions as in the messages: 'Traffic Delay Ahead' or 'Wind Gusts on Bridge'. These displays could improve comprehension of the situation by making available additional information, including the approximate length of the delay or the current wind speed. These could also provide alternative courses of action that might prevent user injury or inconvenience. For example, instead of just reporting 'Traffic Delay Ahead', the sign might also provide the reasons for the delay and the time saved by the use of alternate route(s). Also, advanced navigation systems in vehicles could receive and voice this information.

5.2. Tailoring safety information

In contrast to static signs or labels, dynamic electronic warnings offer the flexibility of changing the physical characteristics and message content of warnings. The information presented can be tailored to the hazardousness of the situation or to the receiver's characteristics to benefit comprehension.

One way in which this could be achieved is by manipulating the physical characteristics of the warning to reflect the level of hazard involved. In the USA, the National Weather Advisory System and, more recently, the Homeland Security Advisory System (HSAS) currently use this method to inform the public of changes in weather and probable terrorist activity, respectively. For example, the term 'Tornado warning' is intended to convey a much more heightened level of risk than the term 'Tornado watch'. Previous work has indicated that different colours have different hazard connotations (Braun *et al.* 1994, Chapanis 1994, Wogalter *et al.* 1998, Smith-Jackson and Wogalter 2000). Red, the colour used by HSAS to indicate the highest level of danger, is typically perceived to be more hazardous or urgent than other colours. Thus, in applications, the colour displayed in a warning could be changed to reflect the current level of danger. Similarly, voice and sound modifications can produce different levels of perceived urgency (Edworthy and Hellier 2000, Hollander and Wogalter 2000).

Comprehension could also be aided by tailoring the warning message to user characteristics. Personalizing the warning content through dynamic modification could offer customized support. For example, the information presented could be tailored to the experience level of the user. Detection of expertise level could involve some of the sensor methods already described in this article, wherein the warning system adapts to the user's demonstrated or desired skill level. Expert users might benefit from the use of technical information, whereas novices may be confused by such content. Indeed, users who are insufficiently skilled could be warned not to use certain equipment without someone more experienced present. In order not to overload the novices, initially they would receive only the most basic information, but over time, as their experience allows, they would receive different, more specific information. More complex systems would allow user-system interactions in real-time with concurrent adjustments in information that the user requests or that the system collaboratively suggests.

Cultural differences can affect warning comprehension (Smith-Jackson and Wogalter 2000). Casey (1993) provides one case report of Kurd villagers in northern Iraq that illustrates how cultural differences can influence comprehension of warning material. Although the skull and crossbones symbol was prominently displayed on cases containing grain for planting but not eating, Kurd villagers consumed the grain and became ill because they did not understand the meaning of the pictorial warnings. When asked, the villagers simply thought that the pictures of the skull and crossbones were USA company logos. This case clearly demonstrates that warnings should be tailored to match or complement users' cultural and personal uniqueness in beliefs and attitudes (DeJoy 1999).

To provide such customization, considerable data must be used and quickly processed to anticipate and present the needed warning information at the appropriate time. As suggested earlier, some systems might be able to 'sense' differences in users' skill levels by evaluating task performance. The system would detect a person skilled to deal with the hazard vs. someone else who is not (as) skilled. For example, when a task is attempted, but is performed incorrectly, sensing devices could issue a warning or even refuse to proceed further until the error has been corrected.

However, personalized systems would likely benefit from specific information about the user before the task is attempted. This could be accomplished by data that the user carries with him/her. Currently, there are 'smart' credit cards that contain user information, and wireless electronic tags that can transmit information within a short proximity (e.g. ExxonMobil's Smart Pass, which identifies credit customers by passing an electronic key near the face of the petrol pump). Consider the extension of this technology, i.e. a wireless device that the user carries with him/her that transmits for short distances information about the person's preferences and characteristics. Such systems could access information stored about the user's skill level before a person actually demonstrates his/her level of ignorance in a task and, thereby, serve to reduce the likelihood of an accident. For example, tags worn by industrial workers could contain personalized information about their expertise and qualifications regarding whether they would be allowed to enter restricted hazardous areas and to use particular hazardous equipment. In future applications, authorized personnel would receive different or no warnings than unauthorized personnel would receive. Thus, someone with a 'visitor's' tag at an industrial facility would be assumed to have inadequate expertise and would receive warnings appropriate for them, which may be different from those that the employees receive (Wogalter *et al.* 1994).

5.3. Technology-enhanced training

Another area where new technology might facilitate warning comprehension is through training. Once a determination is made concerning the user's skill level, training materials can be tailored to meet their needs and abilities. Such systems could also be used to track workers' training performance and could be updated when necessary via Web access. Thus, if a work environment contains a new hazard (or a newly understood hazard), the most current safety information and instructions could be downloaded from the Web and presented.

With current advances in computerized multimedia tools, animated sequences could be included during training to facilitate initial learning and later retention of safety information (Reiber 1994). Warning displays that use animation might also serve as an effective means of communicating metaphor-based hazard information. Metaphorical hazard descriptions are statements that relate other similar events or processes that the user already understands with regard to the hazard being communicated. The potential benefit of metaphors is indicated in a recent study showing that metaphors can increase warning comprehension by presenting information in a manner that is consistent with users' previous knowledge stored in semantic memory (Bowles *et al*. 2002). For example, participants better understood the hidden hazards associated with a wood chipper when it was illustrated as a vacuum cleaner that might 'suck them in'.

In addition, vignette-based warnings designed as a proxy for personal experience might also act to increase warning comprehension (Mayhorn *et al*. in press). With a vignette-based warning, safety information is presented in a short story-like fashion to illustrate the presence of hazards and suggest courses of action to avoid injury. Video-based warnings and virtual reality might also assist hazard training, particularly in delivering realistic warning vignettes. For example, experienced and novice health-care workers might be more effectively trained to wash their hands after contact with each patient if a video of live actors, a virtual reality programme or an animation showed a gradual build-up of micro-organisms on their hands on a typical day in the hospital. While habits are notoriously difficult to change, vivid, persuasive communications using technology might be a salient tool to instruct and remind safe behaviour, such as hand washing by nurses who may not have been doing it over many years of experience.

6. Compliance

An important goal of warnings is to increase safe behaviour and decrease unsafe behaviour by guiding users to make the appropriate decisions and actually carry them out. As seen in the preceding sections, there are a number of factors that could be incorporated into warning systems to facilitate noticing, encoding and comprehension. A similar set of factors plays a role in facilitating compliance. One example is a video that can allow users to see how a task can be accomplished safely, thereby modelling how to behave appropriately. Indeed, research shows that participants are more likely to imitate warning compliance when they view a video tape showing a model carrying out the correct behaviour compared to a static warning sign instructing the same behaviour (Racicot and Wogalter 1995).

Presenting content that motivates users to comply with the warning can be added to technology-based warning systems. For example, research suggests that including information that provides the severity of consequences motivates compliance (e.g. DeJoy, 1999). Therefore, incorporating explicit information concerning how bad the injury might be into technology-generated warnings should increase safe behaviour.

6.1. Increasing compliance through personalized warning information

Personalized warnings, which have been described as potentially useful at earlier stages of the warning process, can also benefit the performance of compliance behaviour. Research shows that personalized warnings that incorporate the target-receiver's name (instead of a signal word) produce higher rates of compliance of donning protective equipment of users performing a chemical mixing task (Wogalter *et al*. 1994). Part of the reason compliance may be benefited in the above study is that including the user's name adds relevance; otherwise, users may believe the warning is not necessarily directed to them. By applying this idea, future technology could personalize warning content. For example, the 'smart' card described earlier could provide name and other personal information to the system. Additionally, smart living environments could employ a voiced presentation that speaks the user's name. Alternatively, a video recording of a model with characteristics similar to the user could display safe behaviour and warn against unsafe behaviour.

Decision-making support might be provided to make specific situational recommendations based on information gleaned from sensor data. To illustrate, researchers at the Veterans Administration Hospital in Atlanta, Georgia recently developed an expert system to make recommendations concerning exercise regimens for older adults (Boyette *et al.* 2001). An advanced warning system with access to such an expert system could monitor older adults' vital signs through a wearable sensor and then warn or actively intervene to stop exercise, if necessary, should the heart rate rise above acceptable limits.

6.2. Reducing the cost of compliance

Video displays that demonstrate safety procedures may serve to benefit compliance behaviour because they can reduce the amount of cognitive effort users must put forth to learn the correct procedures. Research shows that compliance is more likely when the directed behaviour is relatively easy or, in other words, cost of compliance is low (Wogalter *et al.* 1987, Wogalter *et al.* 1989, Dingus *et al.* 1991, Hunn and Dingus, 1992). Clear, unambiguous presentations would reduce cognitive load to process the information and decrease misunderstandings that might result in incorrect procedures being performed.

Such systems could also make safety equipment more accessible and thereby reduce the cost of compliance. For example, a warning system where industrial chemicals are used or processed could communicate the location of protective goggles to increase warning compliance.

7. Conclusion

Future technology-based warning systems promise to provide improved access to safety information and cognitive support for each of the components of the warning process. Specifically, the goal of improving user safety through higher quality risk-related decisions can be accomplished by capitalizing on the interactive capabilities of technology and its ability to personalize warning information through dynamic modification of content.

7.1. A systems approach to warnings design

Many of the potential applications of technology can be combined to support the entire warning process, not just particular components. Consider the cognitive support offered by a warning system that alerts users to a leak in a water pipe on their property based on information from water pressure and moisture sensors. As a result, warning information could be transmitted to broadband Internet and be automatically downloaded to the property owner's PDA. The PDA's auditory alert would provide the initial cue for the receiver's attention to be drawn to the unit. Then the warning information on the PDA's video display could hold the receiver's attention, thereby supporting encoding. Tailored warning and training presentations would enhance comprehension by shaping the material so that it is in accord with the user's attitudes and beliefs (e.g. whether the leak is worth worrying about). Finally, clear communication concerning the severity and cost of non-compliance (e.g. loss of property) should affect the likelihood of compliance to do or not do something about the leak. Obviously, this particular warning system would not be very effective if the user has turned off or forgotten his/her PDA. However, future wireless technology, such as interactive electronic tags and remote kiosk-like systems, promise to facilitate safety communication by bypassing the limitations of current technology.

This holistic approach to technology-based warning design is consistent with the systems approach that pervades the field of human factors/ergonomics (e.g. Sanders and McCormick 1993, Helander 1997, Laughery and Wogalter 1997). As with the design of any system, technology-based warnings should consider the user, the environment and the technology involved. Development of dynamic, flexible warning technologies that can tailor information to meet the needs and characteristics of individual users epitomizes the systems approach. One obvious benefit to personalization of warning information is the increased likelihood of compliance, resulting in hazard avoidance. Another benefit lies in the improved accessibility of safety information for populations with special needs, such as older adults or people with disabilities.

7.2. Implementation costs

Together with the benefits of technology come literal and intellectual costs. One potential problem is the issue of access to technology. Currently, some segments of the population do not know how to use nor can afford technologies such as the Internet and wireless communication devices. This so-called 'digital divide' has the potential to leave some people at greater risk to hazards than others. Therefore, it is important that technology-based warning systems not necessarily replace existing delivery mechanisms, but rather supplement them – at least in the near future. Another potential problem with technology-based warning systems is the invasion of individual privacy. While the types of detection systems described here would certainly benefit people in terms of their knowledge of hazards and how to avoid them, technology has the potential to be intrusive by interrupting other important cognitive processing and by affecting privacy rights. One solution, for example, is to ask for the user's permission before recording or sending the information. The balance between privacy and security is an issue that must be addressed in the years ahead, not just with regard to warnings but also in other areas of life influenced by technology.

Lastly, the discussion presented here was not meant to provide a comprehensive review on all the ways technology-based warning systems could be implemented. Instead, the goal was to highlight some of the prospective potential benefits of technology and to provide direction for future warning development and research. While much empirical work remains, the promise of more advanced, technology-based warning systems is enticing.

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