To be published in Proceedings of 1999 Human Factors and Ergonomics Annual Meeting

AN ANALYSIS OF PROBLEMS WITH AUDITORY ALARMS: DEFINING THE ROLES OF ALARMS IN PROCESS MONITORING TASKS

Yan Xiao
University of Maryland School of Medicine
Baltimore, Maryland
yxiao@umaryland.edu

F. Jacob Seagull
University of Illinois at Urbana-Champaign
Champaign, Illinois
seagull@uiuc.edu

It has become a standard practice to use auditory alarm devices to enhance human monitoring performance in monitoring tasks. However, the effectiveness of such practice has been-challenged from time to time, which leads to the fundamental question of what roles alarms should and could assume. This paper reviews reported observations of interactions between human operators and alarm mechanisms in patient care, aviation, and process control. Based on the reviews, we propose that the roles of alarms in process monitoring tasks should be viewed more as a way of informing process status and less as a way of interpreting the significance of process status. The roles can best be understood in the skill-, rule-, and knowledge-based performance framework. Implications to alarm and auditory designs are discussed. Specifically, design of alarm devices should be guided by the principle of information provision regardless of whether an alarm may be true or false indication of "alarming" events.

INTRODUCTION

Designers of human-machine interfaces have long adopted the practice of attaching alarms of various types to displays and devices. In many senses such practice is well-intended: it aims at well-known limitations in human performance, such as limited attention spans and difficulties in tracking many parameters. Control room operators can be warned of leaking valves; anesthesiologists can be warned of disconnection of ventilating circuits; pilots can be warned of low fuel levels; train operators can be warned of over-heated engines. The utility of alarms was supported, for example, in a closed claim study on patient monitoring (Tinker, et al., 1989).

On the flip side, however, in almost every work setting in which alarms are deployed, there are also reports of inappropriate alarms. The problems with alarms have been many. Their acoustic properties are often poorly designed (e.g. Fromm, et al., 1995; Loeb, et al., 1992; Momtahan, et al., 1993) but more importantly, there seems to be a general lack of understanding of what kind of information auditory warning signals provide. As a consequence, the design of auditory warning signals is driven often if not mostly by what is technically possible and by legal concerns, rather than by the requirements for providing relevant and timely information to human operators. On one hand, profusion of auditory alarms with dubious informational value in many settings has raised the concern of true alarms being ignored or discounted and has been associated with noisy (Cropp et al., 1994) and stressful working environments (e.g. Topf & Dillon, 1988). On the other hand, auditory channels are an important means for human operators to extract information and to monitor the underlying processes; these channels may have not been effectively exploited.

In this paper, we will review observations on the interaction between human operators as process monitors and alarming devices in several domains. The term "alarm" is used to describe various events, actions, responses, and states, and a concise definition is difficult to pin down (see Stanton, 1994; a definition is quoted below). This paper is to focus on devices that provide information on the monitored process; auditory alarms are those sounding mechanisms associated with the monitoring devices. Based on this review, we will examine several definitions and conceptions of alarm. We believe that part of the problems with the current state of affair of alarm design is due to the lack of distinctions of various roles alarms perform.

PROBLEMS WITH ALARMS

In order to illustrate the importance of distinctions among different roles of alarms, we will first review several categories of reported problems with alarms. To focus on the information value of alarms, we will ignore problems specific to the acoustic or visual properties (e.g. too loud).

False alarms

In most domains the base rate of loss of system integrity is low. However, due to the potential consequence of such events, designers often adopt the philosophy of "better be safe than sorry". There are numerous reports on the problem of false alarms in medical care (e.g. Meredith & Edworthy, 1995; Kestin et al, 1988; Xiao et al, 1996) and process control (e.g. Kragt & Bonten, 1983). The high rates of false alarms or low positive predictive values have been shown to degrade the performance of human-machine systems (Sorkin & Woods, 1985; Lawless, 1994; Breznitz, 1984; Bliss, Gilson & Deaton, 1995; Bliss, Dunn & Fuller, 1995). Several factors contribute to this problem. Interferences and reliabilities of transducers are among the more significant contributors (e.g. cautery machines producing artifacts in electrocardiograms). Other significant factors include those associated with connection and calibration of monitoring devices.

Nuisance alarms

Or "wrong context" alarms. Sometimes these alarms are also labeled as false alarms due to their perceived absence of value to human operators. Nuisance alarms are those indicating state changes that are potentially dangerous to system integrity in some context, but not in the context in which they are set off. For example, when the ventilating circuit to a patient is disconnected intentionally (as in suctioning the patient's breathing airway), the disconnection alarm goes off. In general, human operators often need to change (or maneuver) process profiles (as in landing of an aircraft, anesthetizing a patient and shutting down a power plant), alarms designed to indicate abnormal system states often go off due to insensitivity to the context of operation (Woods, 1995; Kragt & Bonten, 1983; Xiao et al, 1996).

Inopportune alarms

Or "wrong time" alarms. During major disturbances in a system operation, alarms associated with many parameters are set off (e.g. “cascading alarms”). Most of the alarms indicate minor deviations that otherwise are of interest to the operators during normal operation but not during a major disturbance. The operators can be overwhelmed by the sheer number of alarms, even though only one or a few of them are worthy of immediate consideration by the operators (e.g. Bye, Berg & Owre, 1994; Mackenzie et al., 1994; Marshall & Baker, 1994; Patterson, 1990; Sorkin, 1988; Stanton, 1994).

Not surprisingly, efforts have been directed at addressing these problems. A major focus seems to be on the reduction of the amount of alarms (e.g. the HALO approach described in Bye et al., 1994; Block & Schraaf, 1996; Schreiber & Schreiber, 1989; Uckun, 1994). Other approaches aim at proper acoustic profiles of alarms. (e.g. Edworthy & Stanton, 1995). Some guidance for developing "state-of-the-art" alarm systems in different domains currently is available from sources such as the International Standards Organization's (ISO-9703-2), the Nuclear Regulatory Commission (O’Hara, et al., 1994), or the Food and Drug Administration (AAMI, 1996).

While critiques abound about the problems reviewed above, observations have shown that human operators make use of the alarms in ways other than being informed of system instability (Stanton, 1994a, 1994b; Vicente, 1996). Kragt & Bonten (1983), for example, found that alarms are used to locate co-workers. Woods (1995) described a situation in which the operator complained about the removal of a source of nuisance alarms. In that siuation, scheduled change of operation occurred and such change used to cause alarms to go off. After removal of such alarms, the operators did not receive any indication of change of operation at all.

These problems indicate a fundamental conflict: (1) operators may be interested in knowing the underlying changes, but not interested in the alarm mechanism’s interpretation of the changes (i.e. "These changes are just fine, don't alarm!"), and (2) the alarm mechanism treats all alarms as important regardless of the operators' priorities or the contextual importance.

AN ANALYSIS OF THE PROBLEMS WITH ALARMS

From the brief review above, it appears that a fundamental shortcoming of many of the alarm problems is with the **interpretation** of the significance of a state change in the monitored process. This is important since alarms are designed to address limitations of human performance, particularly those associated with attention, but not with judgment.

In a seminal paper, Rasmussen (1983) drew several important distinctions. One of the distinctions is how a human operator perceives a displayed parameter, which can be used as (1) a signal to drive psycho-motor activities, (2) a sign to trigger the initiation of operating procedures (standard or otherwise), and (3) as a symbol to trigger goal-oriented activities such as diagnosis and planning. This distinction is important to the current analysis of alarms because it illustrates that a change in the monitored process can be **interpreted differently**, and invokes different kinds of behavior depending on the larger context. In this sense, the designers of alarms impose *a priori* interpretation of a change in a monitored process, in addition to providing a mechanism for the detection of such change. What is even more problematic is the situation in which the designer only provides the interpretation, but hides the underlying change in the monitored process (for the purpose, for example, of **reducing** the "clutter" or amount of data presented to the operator). Another solution is to have intelligent alarms that integrate many alarms. The danger here is that the system becomes so complex that it is difficult for human operator to reason **backwards** why the intelligent system "thinks" the changes are noteworthy according to the designer's *a priori* interpretation (Cf. Woods, 1996 on complexity associated with automation). This cognitive demand can be non-trivial--as in many systems, many intervening components exist between an alarm and a system change. For example, a fault could exist anywhere through (1) changes in the monitored process, (2) transducer, (3) connectors, and (4) monitoring equipment setting and functioning. Often, while the human operator is primarily concerned with the first possibility, there is also interest in knowing exactly where the fault lies in other possibilities.

Thus the fundamental question for alarm design is how to assign the role of alarms: as an indicator of changes (thus when and how to present the changes) or interpreter of such changes (thus what the changes mean). Woods (1995) provided an excellent analysis of problems with alarms from the view point of attention directing. He proposes that a major function of alarms is to direct attention in the context of fault management. Thus when an alarm goes off, the operator is essentially informed: "Attention: You'd better have a look at this to see if action is needed."

A number of failure modes can be anticipated with this role of alarms:

- Nothing is wrong regardless of the context
- Nothing is wrong given the context
- Nothing is wrong because I intentionally made the system to behave like that
- Something is wrong but I know that already
- Something is wrong but I do not need to know about it at this time.
- Something is wrong but it is trivial in any context

Despite the many possible failure modes listed, current alarm system designs often inadequately address these different modes and their implications.

Stanton (1994) proposed a rather comprehensive definition of alarms: an alarm is "an unexpected change in system state, a means of signaling state changes, a means of attracting attention, a means of arousing the operator and a change in the operator's mental state." This definition is significant in that it suggests many roles for alarms other than attracting attention. In many work settings, operators need assistance in multi-tasking attention management. These needs are many and varied, and some examples of the types of assistance that alarms can provide are listed below:

Status displays:

- Auditory display of the status of the monitored process: an often perceptually economic way to deliver information

Interrupts:

- A reminder to do or to check (Guerlain & Bullemer,1996)
- A source of reassurance of system's functioning (Marchall & Baker, 1995)
- An indication of action feedback (Kragt & Bonten, 1983)
- An alert of status change
- A warning of danger
- A direction for attention in fault diagnosis

Aids designed to ameliorate human limitations:

- Short-term memory limits (tracking of multiple threads of activities and events)
- Attention limitation (only attends a small number of information channels)
- Reasoning capacity limits (only considering a small number of factors)
- Sustained attention span limits (only able to be vigilant for short period of time)
- Long-term memory limits (interpretation of signal importance in terms of reliability in recall and speed in recall).

Guidance which may, using Rasmussen's (1983) framework, be understood as assisting:

- Knowledge-based behavior: something is wrong here --- please diagnosis and evaluate the system's stability

- Rule-based behavior: Upon hearing this sound, turn off the valves.
- Skill-based behavior: Modulate your input according to the rate of auditory alarm soundings.

It should be clear from the above lists that the function of alarms should not be relegated to the simple task of warning of danger. Their potential function as status displays, interrupts, aids for human limitations, and sources of problem-solving guidance should all be considered in the design of alarm systems.

DISCUSSION

Previous studies (e.g. Vicente et al, 1996; Roth et al, 1997**;** see also Morray, 1997; Stanton, 1994) have demonstrated that monitoring is not a passive task in which the operator waits for dangerous situation to develop. Rather, monitoring task often is a process of maintaining situation awareness (e.g. Gaba & Howard, 1995). As a result, auditory signals, including alarms, may perform functions of information provision other than alerting.

Many possibilities exist for dramatically improving the effectiveness of alarms in the area of providing useful information to operators. Examining these possibilities requires detailed study of how human operators make use of information and how the information should be presented. As an example of one potential improvement, the auditory channel may be used not for auditory warning signals, but rather for “display” of continuous status information, as in the case of pulse oximeter in patient vital sign monitoring. In this case, the pitch of the auditory tone of a pulse oximeter is used to display oxygenation levels of the patient, thus keeping human operators better informed.

In some process monitoring tasks, the human operator is assisted serendipitously with auditory displays. One example is the monitoring patient ventilators. Some ventilator models produce sounds of the pneumatic mechanism. The rhythm and pressure of the ventilator can be heard. Without looking the clinician can monitor the ventilator in the background. Another example is the mechanical counter of the control rod position. Changes of the counter produce clicking sounds, thus allowing the operator to know, without looking, where the rod position is changing and how fast. Gaver (1993) described an interesting testing case of utilizing sound to display the operating status of a simulated bottling plant. Future exploitation of auditory display should be carried out to maximize the use of the auditory channel.

In summary, our analysis of the problems with alarms suggests that designers of alarm systems should focus on information provision, rather than the interpretation of system changes. Human operators need better informed of what has changed, in addition to or maybe instead of what that change may signify.

ACKNOWLEDGMENT

Preparation of this paper was supported in part by a grant from the National Patient Safety Foundation at the American Medical Association and from University of Illinois. The authors wish to thank the contribution from Chris Wickens and the reviewers for their comments.

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