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Tailoring reveals information requirements: the case of anaesthesia alarms

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Abstract

We discuss the phenomenon of system tailoring in the context of data from an observational study of anaesthesia. We found that anaesthetists tailor their monitoring equipment so that the auditory alarms are more informative. However, the occurrence of tailoring by anaesthetists in the operating theatre was infrequent, even though the flexibility to tailor exists on many of the patient monitoring systems used in the study. We present an influence diagram to explain how alarm tailoring can increase situation awareness in the operating theatre but why factors inhibiting tailoring prevent widespread use. Extending the influence diagram, we discuss ways that more informative displays could achieve the results sought by anaesthetists when they tailor their alarm systems. In particular, we argue that we should improve our designs rather than simply provide more flexible tailoring systems, because users often find tailoring a complex task. We conclude that properly designed auditory displays may benefit anaesthetists in achieving greater patient situation awareness and that designers should consider carefully how factors promoting and inhibiting tailoring will affect the end-users' likelihood of conducting tailoring.

Keywords: Alarms; Tailoring; Interface design; Situation awareness; Auditory display; Sonification

1. Introduction

The modification or 'tailoring' of devices, tasks and systems is a well-recognized phenomenon in the study of human interaction with engineered systems. Tailoring occurs

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when a device, task or even an organization is modified during use to act in a way that may not have been envisaged when it was originally conceived by the designers (Cook and Woods, 1996; Mørch and Mehandjiev, 2000; Obradovich and Woods, 1996; Rendell, 2003). Tailoring may be performed to achieve a goal that the original design did not fully support or modify an existing device, task or organization to support a goal that was not originally anticipated. In the interactive systems design community there is an increasing emphasis on developing systems that can provide tailoring flexibility to appeal to a greater range of end-users. Much of the prior work on tailoring has focused on designing environments that encourage end-user tailoring (Mørch and Mehandjiev, 2000). Using the anaesthesia domain, we examine the factors promoting and limiting tailoring and advocate that examples of tailoring can be used to guide revolutionary display design rather than systems tailoring design.

The interfaces of some systems have been made flexible so that users can make adjustments and do tailoring with end-results that may or may not have been envisaged by designers. Such systems include computer operating systems (Mørch and Mehandjiev, 2000), process supervisory control and data acquisition systems (Guerlain and Bullemer, 1996; Mumaw et al., 2000), glass cockpits (Weiner, 1989) and medical patient monitoring equipment (Cook and Woods, 1996; Obradovich and Woods, 1996; Watson et al., 2000b). Most of these systems have been designed with a focus on tailoring visual displays; however, some systems allow auditory displays to be tailored as well. In most cases where tailoring has been allowed, designers have recognized the need for the end-user to extend the system beyond the initial specifications.

The need to make systems flexible reflects the difficulty in clearly identifying all tasks and activities that end-users may need to achieve. Interestingly, the way people tailor their technology may provide clues for what the interactive experience really should be like. By identifying what people are trying to achieve through tailoring—the workload people want to carry, the activities they want or have to do concurrently, how often they need information and what information is common to each task—we can focus on supporting these needs in the underlying design, reducing the need for the end-user to tailor the system. We do not argue that designers should remove the ability to tailor or that further problems will not emerge that can be alleviated through tailoring (Rendell, 2003). Rather, we argue that we should examine tailoring for its implications for redesign as much as for further flexibility.

In this paper, we take problems with anaesthesia auditory alarms in the operating theatre as an example of how interactions with technology can guide us towards what the technology should actually do. We report an observational study of 42 surgical operations in which we study anaesthetists' responses to alarms. Then with the help of an influence diagram model we walk through some detailed examples of how experienced anaesthetists tailor the alarm systems to provide themselves with a better environment for patient monitoring. We then draw implications for auditory displays more generally.

We contend that although tailoring sometimes lets anaesthetists provide a better level of patient care, it is rarely used because of the complexity of the domain and the high workload of tailoring. Rather than improving the ability to tailor in such environments, designing better auditory displays could provide better levels of patient care without requiring an anaesthetist to have expert knowledge of how to tailor the monitoring system.

2. A study of auditory alarms

In this section we survey problems with auditory alarms and present a study examining anaesthetists' responses to alarms. In Section 3 we describe the tailoring activities we observed, characterizing them with a model of attentional load in the operating theatre.

Many papers have appeared on the confusing nature of alarms in different domains (Stanton, 1994; Stanton and Edworthy, 1999). The dangers of having too many non-discriminating alarms in medical critical care environments have been of particular interest (Cropp and Woods, 1994; Meredith and Edworthy, 1994; Seagull and Sanderson, 2001a,b). The rapid rate of technical development in patient monitoring equipment has led to a proliferation of alarm systems in the operating theatre. The increase in the number of alarms and the lack of discriminability between alarms make it difficult for operating theatre staff always to be sure of what an alarm specifies.

Since alarms are not automatically situation-dependent and since anaesthetists must integrate a series of separate systems, many alarms are ambiguous and are considered a nuisance. As a result, auditory alarms that are intended to increase anaesthetists' situation awareness by directing their attention in an effective way are instead increasing anaesthetists' workload with little tangible benefit.

One argument is that if alarms could be adjusted to appropriate levels for each situation, then they could act to effectively control attention and improve the anaesthetist's situation awareness. However, situation-dependent alarms could only be achieved using intelligent alarm systems or by relying on the anaesthetist to make the adjustments to the alarm settings. There are many problems with intelligent alarm management systems, including the need for highly reliable sensors and for situation-specific information. Solutions to these problems are years away. Flexible alarm systems are already in use; however, it is important to understand both the sources of the alarms and the flexibility in the alarm systems to develop an appreciation for why anaesthetists may or may not tailor their alarm systems.

We investigated the problems of auditory alarms in the operating theatre to identify why alarms from anaesthesia equipment are failing to provide appropriate support to anaesthetists. Here we report findings from an operating theatre observational study in large metropolitan teaching and research hospitals (Watson et al., 2000a). Our goal was to gather information about responses to alarms as a basis for finding a way to reduce the noise, confusion, and even danger they sometimes create in the operating theatre. The results from the study demonstrate not only that most alarms failed to produce an overt response from the anaesthetists but also that anaesthetists need auditory displays to indicate more than simple breaches of limits.

2.1. Data collection

In a study conducted over a 2-week period in two large metropolitan teaching and research hospitals in Australia, we observed 15 anaesthetists during 42 separate operations. The operations varied in length, operation type and in the monitoring equipment used by anaesthetists. Three different anaesthetic machines were observed. Our focus was the anaesthetists' responses to alarms from the anaesthesia machines and monitors. Information displayed on visual monitors was captured using a hand held video camera. The observer recorded the anaesthetic alarms and the anaesthetist's responses to them.

2.2. Data reduction and findings

In the subsequent data reduction, we noted the number of times an alarm limit was breached and the number of times auditory signals sounded. We noted whether auditory alarms successfully directed an anaesthetist's attention to a problem with the patient or with the anaesthetic machine. We also noted when anaesthetists manipulated auditory alarm systems to monitor the patient.

Overall, 1358 patient monitoring alarms occurred during the 42 operations. The alarms were divided into alarm sounds indicating the initiation or first sounding of a specific alarm event (481; 35.4%), and the remaining 'run-on' alarms (877; 64.6%) that continued to advise of the initial alarm (see Venn diagram on the left in Fig. 1). Only 3.4% of all alarm sounds caused the anaesthetist to actively make adjustments to change the patient's state. The anaesthetist responded to the majority of the alarms requiring such adjustments on the first sounding of the alarm—1.9% of the total auditory signals. The number of alarms observed may have been even greater if the anaesthetist had not, in some cases, switched off all anaesthetic alarms before the operation started. Post-operative discussions highlighted anaesthetists' discontent with the current alarm system.

Alarms caused problems during periods of high workload, such as the induction and emergence phases of operations, and when anaesthetists have to deal with unanticipated patient events. The problems of alarms were clearly illustrated in one operation, during which a patient experienced complications (Operation 9, May 1998). As the incident started to evolve, the anaesthetist delayed attending to a patient while he waited to silence the impending alarm.

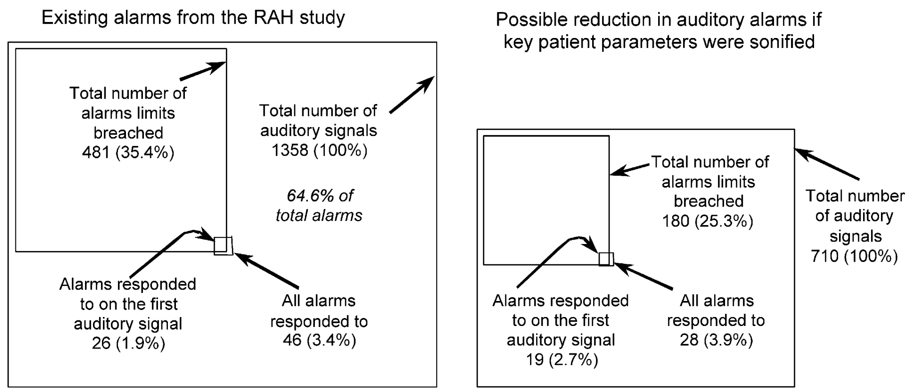

Fig. 1. Observed responses to auditory alarms in the OR (modified from Watson et al. (2000a)). Right part of figure is discussed later in paper.

The results from the field study and personal communications with several anaesthetists indicated that the auditory alarms regularly failed to effectively direct attention and even interfered in effective patient monitoring. Although the present sample size was small, practices may differ across locations, and our sampling of anaesthetists' opinions may be unrepresentative, we have had similar criticisms about alarms from anaesthetists at the five hospitals across two states that we have worked with and the second author has reported similar findings from the US (Seagull and Sanderson, 2001a). Similar examples can be found in other environments where auditory alarms are used to direct attention (Mumaw et al., 2000; Stanton, 1994; Meredith and Edworthy, 1994; Stanton and Edworthy, 1999). Since anaesthetists are continually monitoring the patient's reaction to surgical and pharmacological stimuli—focusing on physiological trends to predict possible incidents and plan possible future interventions—fixed alarm ranges are inadequate in supporting the anaesthetist's awareness of patient state.

The failure of alarms to effectively direct attention in the operating theatre is partly attributable to the large variation between patients. Physiological parameter readings that are normal for one patient may be abnormal for the next because of many factors, including age, gender, physiological condition and the surgical procedure to be conducted. One possible response is for the anaesthetist to 'tailor' the alarms to match the patient's state better. We will examine tailoring in Section 3.

3. Tailoring auditory alarms

In this section we discuss some examples of alarm tailoring found in our study in the context of a simple model of demands on attention, with a view to drawing implications for system redesign. In mission critical environments, there is usually enough flexibility in information and control systems to let operators tailor their interface. Several examples of complex system tailoring already exist that demonstrate the advantage of having such flexibility (Guerlain and Bullemer, 1996; Mumaw et al., 2000; Cook and Woods, 1996; Obradovich and Woods, 1996). Selecting appropriate alarm settings for particular phases or types of operations may increase the relevance of the alarms when they sound and reduce the number of nuisance alarms.

Many patient monitors and anaesthetic systems already support tailoring to some degree and some are flexible enough to support tailoring by end-users for situations the designers may not have anticipated. There is only a little evidence, however, of anaesthetists making recourse to tailoring across many operations (Watson et al., 2000b). Table 1 shows the main factors that affect whether anaesthetists choose to tailor alarm systems. The first four factors promote tailoring, whereas the last four factors inhibit tailoring.

The fact that tailoring is not always undertaken suggests that, in practice, the opportunity to tailor may not be sufficient to promote tailoring. One or more of the last four factors in Table 1 are deterring anaesthetists from tailoring the alarms to improve auditory information.

Table 1 and our own observational study suggests that simple tailoring actions that are easy to learn and that do not involve a high workload to complete are more likely to occur

Table 1
Factors promoting and inhibiting tailoring

Factors promoting tailoring	
Workload reduction	Supporting better individual and collaborative work performance
State identification	Provide additional information without increasing mental workload
Attention allocation	To guide visual information gathering without having to remembering where to look
Novel state diagnoses	To confirm/reject hypotheses about novel states
Factors inhibiting tailoring	
Flexibility	The level of customization and/or integration available in the system
System functional transparency	Visibility to the user of how to manipulate, customize or integrate the system
Tailoring workload	The difficulty in customization and integration of the system
Self-confidence	The user's confidence in their ability to tailor the system

than complex tailoring that involves detailed knowledge of the system. Simple auditory tailoring, such as turning off or repeatedly silencing patient monitoring alarms, is a practice commonly used by anaesthetists (Xiao et al., 2000) and has also been noted in intensive care (ICU) environments (Rendell, 2003). Often these practices are ritual in nature and may not always be appropriate when used. Mørch and Mehandjiev (2000) observe that ritual tailoring typically originates in the practices of highly skilled end-users who are knowledgeable about both the domain and the interface. Such end-users may have shared with less knowledgeable colleagues their tailored design, but not always the reasoning behind it (see also Cook and Woods, 1996). Since ritual tailoring may persist even after the originator of the tailoring has left the organization, such tailoring may be problematic in working environments, such as hospitals, where on-the-job training is a major part of a person's career development. Ritual tailoring as well as more purposeful tailoring can help people extend systems beyond the designer's intentions; however, there are potential costs associated with the tailoring.

3.1. Influence diagram

We have developed an influence diagram to explore when and why alarm tailoring occurs and to investigate why it is rare for anaesthetists in the operating theatre to tailor their alarms (see Fig. 2). We will use several examples from our observational study to demonstrate how anaesthetists are required to trade off increased workload for higher levels of situation awareness.

At left on the tailoring influence diagram are factors associated with the anaesthetist's situation awareness of the patient and anaesthetic equipment. At right are some

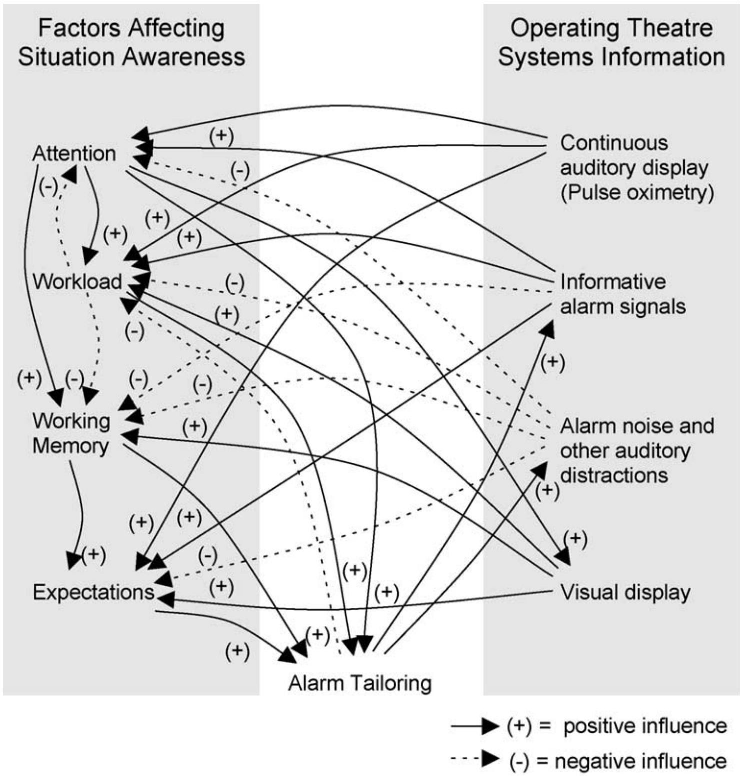

Fig. 2. Influence diagram of factors affecting situation awareness and sources of information in the operating theatre. Specific cases will invoke a subset of linkages only.

information sources in the operating theatre. Other forms of patient information have been omitted, such as patient history, the type of operation being carried out, clinical examination and communications with other operating theatre staff. The four sources of operating theatre system information at right are as follows:

- *Continuous auditory displays*. At present, the only continuous auditory display is the pulse oximeter in which the rate of continuous beeps is mapped to the patient's heart rate and the pitch of the beeps is mapped to the patient's oxygen saturation. The pulse oximeter display does not intrude as alarms do because its continuous sound provides anaesthetists with trend information. A drop in pitch—oxygen saturation—often leads to a rapid response by anaesthetists, thereby effectively supporting the return of attention to the visual display. The continuous nature of pulse oximetry also helps to confirm for the anaesthetist the rate of change for heart rate and oxygen saturation and therefore provides information relevant to the anaesthetist's expectations. Since the display is continuous it does not interrupt activity in the same manner as alarms. Pulse oximetry is therefore consistent with Woods' (1995) emphasis on the importance of supporting pre-attentive awareness of the patient situation.

- *Informative alarm signals*. Alarms are designed to attract attention. Informative alarms may draw anaesthetists' attention to visual information that indicates unexpected changes about the patient or anaesthetic machine. Useful alarms may also be alarms that confirm the rate at which a patient's vital sign are expected to move into an abnormal range (see Fig. 2). Both nuisance and useful alarms have a negative effect on working memory because, by their very nature, they are designed to act as an interrupt.
- *Alarm noise and other auditory distractions*. Nuisance alarms may distract the anaesthetist by moving focal attention to irrelevant visual information. The alarm may indicate a parameter range that is not abnormal or unexpected given the patient's current state. Other auditory distractions may be caused by operating theatre equipment when alarms are not related to the patient's state.
- *Visual displays*. Visual displays provide important information about the patient's state and possible future states; however, this information is only useful if it is in the anaesthetist's field of view.

The four factors affecting situational awareness at left of Fig. 2 are as follows:

- *Attention*. Management of attention is an important factor in maintaining situation awareness in the operating theatre. Anaesthetists must divide their time between many tasks, including monitoring the patient, maintaining the patient's state through pharmacological and physical interventions, and planning and preparing for events in the current and next operations.
- *Workload*. High workload may occur during intubations, extubations and emergencies where anaesthetists need to effectively prioritize their activities and avoid unnecessary distractions. As workload increases, the anaesthetists' ability to allocate time to assessing patient information on the visual monitor will decrease.
- *Working memory*. Activities requiring concentration, such as drug calculations or the placement of a central venous pressure line, may need to be executed in a brief period of time. Attention-demanding auditory signals, such as alarms, may affect some anaesthetists' ability to focus on such tasks.
- *Expectations*. The anaesthetist's expectation of the patient's state is important in interpreting the meaning of different visual and auditory information. Deviations from expectations act as an alert for anaesthetists to reassess the current situation and determine what, if any, intervention should be made. The rate at which a patient's physiological measures move away from the anaesthetist's expectation also helps the anaesthetist diagnose what is happening to the patient and how much time remains before they must commit to a course of action.

The influence diagram in Fig. 2 can be used to analyse examples of alarm tailoring to provide insights into the kind of information anaesthetists need for a better operating theatre working environment. Fig. 2 shows all sources and most possible linkages, whereas the specific examples of tailoring that follow will involve only a subset of nodes and linkages. In Section 3.2 we will examine motivations for tailoring, presenting some case studies with the help of the influence diagram. We will then examine the effect of end-user competence on tailoring and outline the limitations on tailoring.

3.2. Tailoring to reduce operating theatre noise

The most common form of alarm tailoring is to reduce operating theatre noise by turning off all alarms before or during an operation (first factor in Table 1). Although the Australian and New Zealand College of Anaesthetists recommends the use of alarms on patient monitoring systems during anaesthesia, monitoring systems are designed to allow the alarms to be turned off. Turning off the alarms during an operation lies outside the designed purpose of alarms. Some anaesthetists report preferring to work with alarms silenced because they find the alarms are a nuisance, increase workload, misdirect their attention and interfere with their working memory. Other anaesthetists report to us that they turn off alarms during some operations because the alarms annoy or distract some surgeons and surgeons who prefer them to be turned off. In both cases, the overall collective working environment may be improved because the benefit of reducing noise may outweigh the potential benefit of the auditory alarms in increasing the anaesthetist's awareness of the patient's state.

In our observational study we observed ritual tailoring during pre-operational setup. Some anaesthetists consider that ritual tailoring practices may make it more difficult for trainee anaesthetists to learn how to select monitor modes, leading to potentially dangerous situations. For example, an anaesthetic registrar may see that a senior anaesthetist turns off the alarms during several operations. If the registrar fails to ask the motive behind the alarm tailoring, they may assume that it is common to turn off the alarms or they may associate turning off alarms with the type of operations in which they observed the senior anaesthetist performing this action. Turning off alarms may be appropriate only for some patients undergoing the operation. Even worse, the alarms may be left off from the previous patient and the practice could be inappropriate for the next operation. This may be dangerous if a low-risk patient is followed by a high-risk patient.

The effect of reducing noise interference is evident in the general form of the influence diagram (Fig. 2). If noisy alarm signals are reduced or removed, then working memory may be interrupted less often. Removing the nuisance alarms may also decrease the number of times the anaesthetist's attention will be directed to the visual display inappropriately, therefore producing fewer interruptions to the anaesthetist and other operating theatre staff. These advantages may be traded off against the possible advantage of the alarms indicating an unexpected event.

In summary, reducing operating theatre noise by turning off the auditory alarms is a two-edged sword. It will reduce the number of nuisance alarms at the cost of possibly missing informative alarms. Providing facilities for operating theatre personnel to turn off alarms to reduce collective operating theatre staff workload is not the highest priority of designers of patient monitoring systems. Instead, the highest priority is probably to provide an alarm system that alerts the anaesthetists when a parameter moves into an ostensibly unsafe region.

3.3. Tailoring to support attention allocation

Tailoring can be used to support the allocation of attention during multi-tasking. During operation 22 of our study, the lower limit alarm on the pulse oximeter was used as a reminder to the anaesthetist to scan the anaesthetic monitor regularly while he was absorbed with other attention-demanding tasks (see Fig. 3). For most patients, oxygen saturation under anaesthesia is normally maintained at 98–100%, but for some patients it runs lower. Saturation less than 98% does not necessarily require immediate intervention but if saturation drops below 90% immediate intervention is almost always required.

In operation 22, the anaesthetist was reading a journal article while monitoring the patient. Reading is an absorbing task and may not be consistent with regularly monitoring the visual display. Because the patient's saturation was steady around 93%, the anaesthetist changed the pulse oximeter lower alarm limit from its usual 90% up to 94%, (Fig. 3). As a result, the pulse oximeter alarm often sounded when the silencing was off. When the alarm sounded, the anaesthetist would silence it again and do a general scan of the anaesthetic monitor before returning to reading. The pulse oximeter alarm was used as a reminder to check other parameters such as blood pressure, electrocardiograph, end tidal carbon dioxide, etc. This practice was repeated for 30 min.

The above example can be described using the concepts in the influence diagram (see Fig. 4). The potential for the anaesthetist to become engrossed in the article could have led

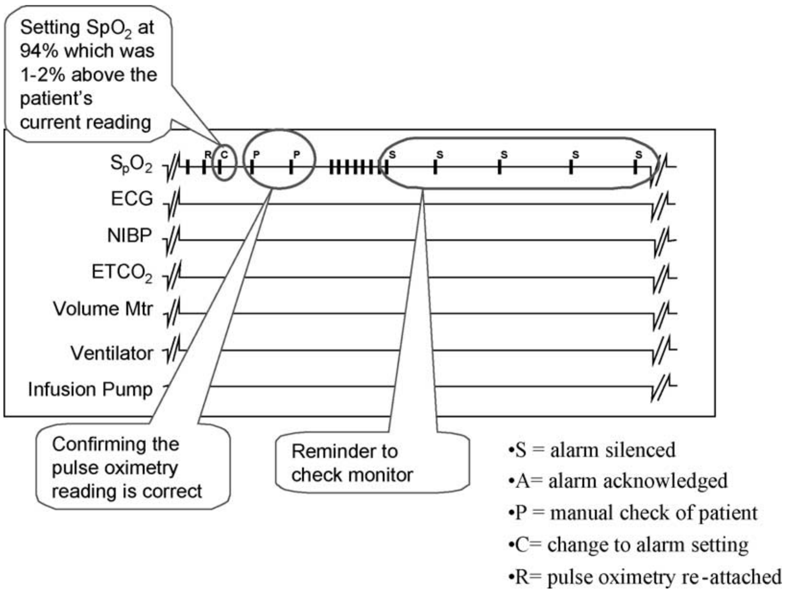

Fig. 3. 'Low oxygen saturation' alarm used as a reminder to check the patient monitoring system (modified from Watson et al. (2000b)).

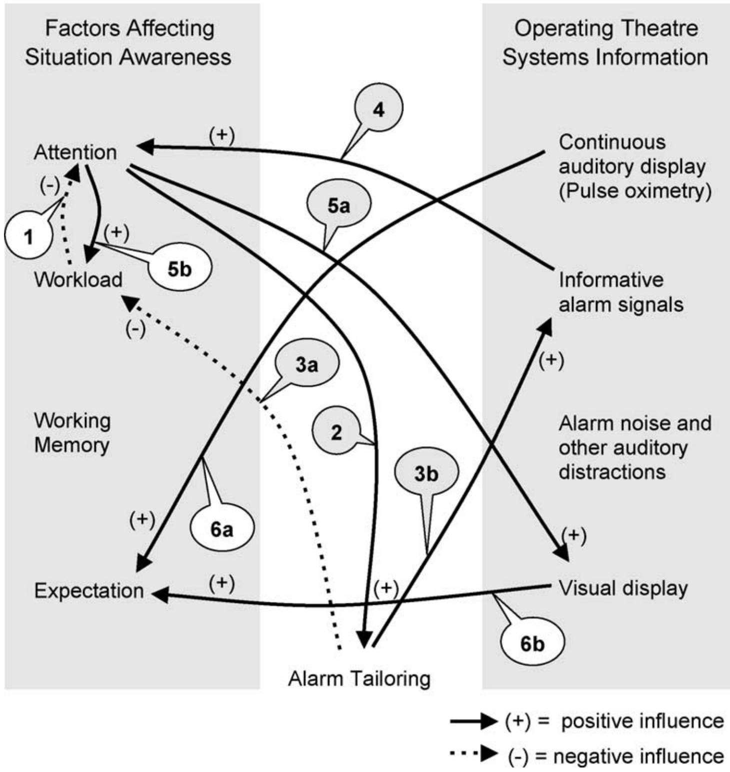

Fig. 4. Influence diagram of how an anaesthetist tailored the oxygen saturation alarm to act as an attention guide.

to lapses in attention critical to the patient's welfare (callout 1). By adjusting the pulse oximeter alarm to a setting higher than the patient's stable oxygen saturation, the anaesthetist effectively creates an alarm system to remind himself to check the visual monitor (callout 2). Workload is temporarily increased while the anaesthetist changes the alarm limits and confirms that the tailoring is producing the desired effect (callout 3a). Since the oxygen saturation (pulse oximeter) continues to alarm unless silenced by the anaesthetist, tailoring the oxygen saturation alarm provides an effective reminder for the anaesthetist (callout 3b).

Once the tailoring was completed, the anaesthetist was free to focus on reading his journal. The oxygen saturation alarm, followed by the anaesthetist's silencing of the alarm, acts as a timer to help the anaesthetist more effectively divide attention between the reading and patient monitoring tasks (callout 4). In this way, the anaesthetist is reminded to check the visual display every time he turns to silence the oxygen saturation alarm (callout 5a), which also frees up cognitive capacity for the reading task (callout 5b). As there is no change in the pulse oximeter, this supports the anaesthetist's expectation that the patient's oxygen saturation is satisfactory (callout 6a) and the anaesthetist's scan of the visual display confirms the expected patient state (callout 6b).

3.4. Tailoring to support state identification

In operation 3, an anaesthetist used the blood pressure alarm as a trend indicator to detect whether his interventions were satisfactorily reducing blood pressure (see Fig. 5). The patient was known to have high to very high blood pressure. From the first intra-operative non-invasive blood pressure (NIBP) reading measurement, a high pressure was identified. The anaesthetist administered drugs to manage the patient's high blood pressure. There were eight audible alarms during induction before the anaesthetist changed the upper alarm limit for NIBP and decreased the interval time between NIBP measurements (not shown in Fig. 5).

During the maintenance phase of the operation, the NIBP reading indicated that blood pressure was rising. The anaesthetist responded by administering further medication to reduce the patient's blood pressure. The anaesthetist ignored the first three alarms while he conducted other tasks. After 1 min had elapsed, he silenced the alarm (indicated with an 'S' above the alarm marker in Fig. 4). This action silenced all alarms on the monitor for 2 min. After 2 min had passed, the alarm sounded and the anaesthetist silenced it once more after visually checking the patient's blood pressure readings on the monitor.

While continuing to conduct other duties, the anaesthetist commented that he was using the auditory alarm to check that the patient's blood pressure was dropping. If he heard the alarm, it would let him know that the patient's blood pressure was still high. The alarm reminded him to check the blood pressure reading on the monitor in the next minute or so when he was free to do so and when the NIBP cuff had taken a new measurement. If he did not hear the alarm, then the drugs were having the desired effect and he could focus on other tasks. After the second alarm silencing, the anaesthetist instead acknowledged the alarm (indicated with an 'A' above the alarm marker in Fig. 5). On the monitor in question,

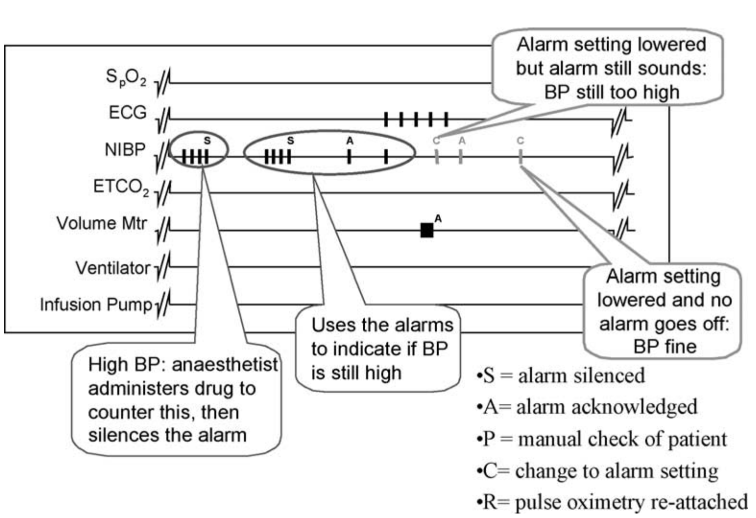

Fig. 5. Blood pressure alarm used as a trend indicator (modified from Watson et al. (2000b)).

an acknowledgment silences the alarm for only 45 s. The anaesthetist used the three alarm responses to observe three different NIBP measurements, which indicated a trend towards an acceptable value for the patient. The anaesthetist reported that he would like to have adjusted the alarm limit so that the system acted as a fine-grained trend indicator, but the 12 steps involved in doing so with the patient monitoring system he was using involved too much work for the purpose.

This example can also be mapped to the influence diagram (see Fig. 6). Knowing the patient had a record of high blood pressure, the anaesthetist knew that regular medication would be required throughout the operation, which was an expectation. During the operation, the patient's blood pressure moved into the high range, even after appropriate medication, and an alarm sounded (callout 1). When increasing the dose of medication, the anaesthetist required confirmation that his treatment was working in the desired way. After the initial fall in systolic blood pressure in response to the medication, the anaesthetist lowered the upper systolic blood pressure alarm level (callout 2). Workload was temporarily increased while the anaesthetist adjusted the alarm settings (callout 3a). NIBP continued to alarm while systolic blood pressure was still higher than the alarm setting,

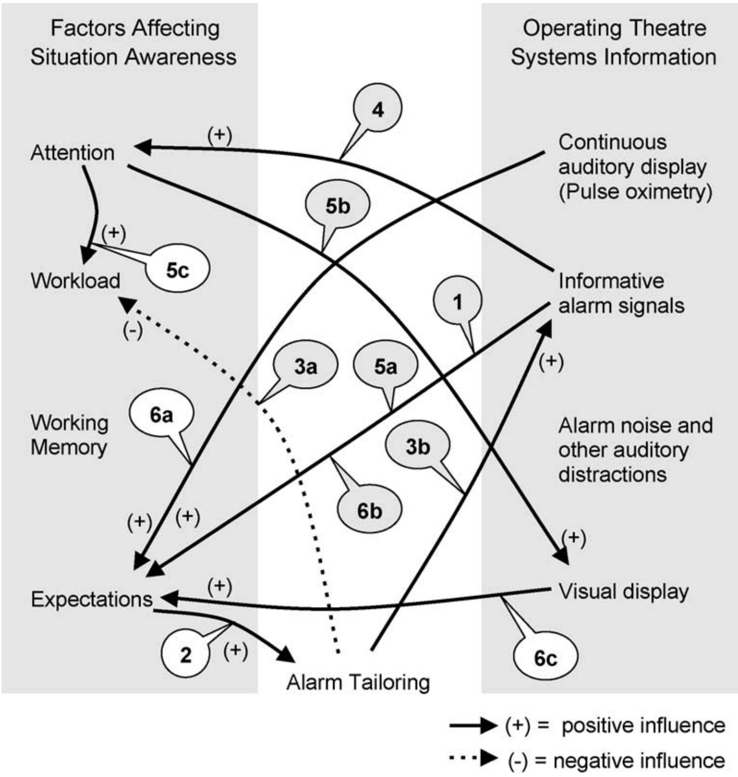

Fig. 6. Influence diagram of how tailoring the blood pressure alarms can increase the anaesthetist's situation awareness by providing information about physiological trends.

unless the alarm was silenced. The continual lowering of the alarm setting by the anaesthetist each time the NIBP alarm occurred, allowed for the alarms to be used as a trend indicator (callout 3b). The alarm, therefore, was made to act as a reminder to check the blood pressure, so directing attention to important information (callout 4). In addition, the NIBP alarm indicated that the blood pressure was still higher than desired (callout 5a). In this way, it also directed the anaesthetist's attention to the visual display (callout 5b) and, as a result, reduced the workload associated with monitoring the rate of change in NIBP (callout 5c).

A lack of any change in the pitch (oxygen saturation) of the pulse oximeter supported the anaesthetist's understanding of evolving events: specifically, that the alarm was likely to be associated with NIBP (callout 6a). The NIBP alarm indicated that blood pressure was still in the abnormal range; however, the absence of the alarm 2 min after the last silencing indicated that the patient's blood pressure had returned to the normal range (callout 6b). The visual display confirmed the rate of change of the patient's systolic blood pressure (callout 6c).

These cases, and others like them, are evidence in the anaesthesia domain of operators tailoring tasks and tailoring systems so that they can carry out their professional activities effectively but without undue stress or workload (Watson et al., 2000b). In the above two examples, an increase in workload was tolerated as it produced information that would improve the anaesthetists' situation awareness. Using the pulse oximeter as a reminder required an increase in workload for only the initial part of the operation. Hence, the workload for the entire operation was actually reduced.

3.5. Constraints on tailoring

As the previous examples indicate, anaesthetists tailor alarms for many purposes. In this section, we outline some constraints that limit how often tailoring is undertaken.

Tailoring requires familiarity with an interface and confidence in its use. After our observational study, the observer asked a senior anaesthetist who had participated in the study, yet had not exhibited any alarm tailoring behaviour, to carry out the activities required to adjust the alarm setting on the anaesthetic monitoring system. Because this anaesthetist had rarely used the patient monitoring system in question, he was unable to make many of the adjustments requested. When asked why he did not tailor the system during operations he gave two reasons. First, he noted that he used several different machines each week with no two machines following the same design philosophy. Since the differences between systems could lead to adjustments made on one machine being incorrect on the next, there was extra work involved and the potential for error. The anaesthetist also commented that remembering how to make the adjustments on each different machine was not worth the effort. Second, the anaesthetist considered the work involved in changing the alarm limits was often too high for short operations and there was the added complication of remembering to reconfigure the machine for the next patient.

The inability or reluctance to conduct anything but the most basic tailoring is common in other domains. During periods of technological or organizational change, whether it involve the introduction of a new piece of equipment or a new procedure, tailoring is more likely to occur. In these cases, tailoring often occurs as a collaborative activity, conducted when effects of the tailoring can be evaluated (Cook and Woods, 1996; Mørch and Mehandjiev, 2000). In other work domains where individuals continue to tailor the system beyond the introductory period, tailoring normally occurs to support vigilance over a substantial period of time (Mumaw et al., 2000). Mission critical systems that evolve rapidly or that involve poorly understood interfaces are likely to limit the possibility for alarm tailoring.

Mumaw et al. (2000) noted that workload regulation was the key feature in making power plant monitoring more manageable. Power plant control room operators clearly benefited when they implemented tailoring strategies. In contrast, in many operations in our study, the possible advantages of increased situation awareness from tailoring were not considered worth the extra workload. In some cases where alarms could contribute to better activity and workload regulation, the user is unaware of how to effectively modify the alarm system to provide an alarm environment tailored to the situation.

The reluctance of people to conduct tailoring is also related to their knowledge of the interface. In collaborative computing environments, Mørch and Mehandjiev (2000) classified users into two categories of tailoring: users and super-users. Super-users normally have an interest in both the technology as well as the tasks the technology is meant to support. Super-users are often pivotal in effectively integrating new technology into organizations and are even able to adapt old technology for new tasks. Super-users are rare, as most users do not have both the model of the work domain and knowledge of how the interface works. In a rapidly developing domain such as anaesthesia, only a few individuals could be expected to achieve the 'super-user' level of knowledge required for complex system tailoring.

The final factor that may dissuade anaesthetists and other operators of mission critical environments from tailoring their alarms is group situation awareness. Cook and Woods (1996) have already noted that by designing tailoring into systems, designers run the risk of reducing the user's control and situation awareness. During emergencies, an alarm system that has been tailored can only support the anaesthetist who conducted the tailoring; others entering the situation may have incorrect expectations associated with the alarms.

In summary, anaesthetic alarm tailoring is rare in the operating theatre because the environment is not conducive to tailoring. Events often happen too rapidly for tailoring to be useful in regulating workflow, especially when anaesthetists conduct a list of short operations. Even when operations are long enough, few anaesthetists are super-users who have enough knowledge of the monitoring interfaces to conduct tailoring. The few examples of tailoring are, however, critical to suggesting what environment anaesthetists would like to have in the operating theatre. These examples suggest that anaesthetists need continuous information about patient state in a format that does not interrupt other activities. The fact that anaesthetists we observed broke up the alarm sounds with periods of silence by using the acknowledge and silence functions indicates not only that continuous sounding of an alarm is unacceptable, but also that only intermittent reorientation of attention is needed for adequate monitoring. The tailoring examples reveal unspoken and perhaps inexpressible requirements for the so-called user experience. They reflect the tacit knowledge anaesthetists have about their cognitive resources, as well as their knowledge of the information needs and performance requirements of anaesthesia monitoring in the operating theatre.

4. Possible auditory display solutions

As noted earlier, designers can respond to instances of system tailoring either by making tailoring easier to perform or by deducing exactly where the existing interface is deficient and making corrections. A more global view is that designers should be trying to provide information in a way that maximizes situation awareness while minimizing distractions and allowing effective workload regulation. Human factors researchers have identified a need to improve the intelligibility of information delivered through sound in mission-critical environments (Woods, 1995; Sarter, 2000; Watson et al., 2000b; Seagull and Sanderson, 2001a; Patterson et al., 1999). In this section, we investigate possible design implications of the tailoring we have observed.

4.1. Continuous auditory displays

In the anaesthesia domain, the fact that visual displays require focal attention means that they will not effectively provide continuous information while the anaesthetist conducts other tasks. Continuous information has to be delivered through some other modality—auditory or haptic—that allows pre-attentive monitoring (Sarter, 2000; Watson and Sanderson, 2004). Sonifications such as the pulse oximeter provide continuous information, so they do not act as an interrupt in the way an auditory alarm does. Only unexpected changes in the pulse oximetry sound are likely to attract attention once a person has become used to its repetitive beeps.

The pulse oximeter has proven to be the most effective monitor in the operating theatre for detecting evolving patient incidents (Findlay et al., 1998; Webb et al., 1993). Changes in its pitch (oxygen saturation) and speed (heart rate) are interpreted with respect to the patient's current and expected state, and they direct attention to the patient or to the anaesthetic system as required. As a result, anaesthetists need spend less time looking the visual patient monitor and overall workload is reduced. The pulse oximeter, therefore, provides information essential not only for the anaesthetist's awareness of the patient's current state but also for the time frames within which decisions have to be made when abnormal patient states approach.

The concepts behind the pulse oximeter can be extended to other physiological parameters. Several authors have suggested using continuous auditory displays—sonifications—to present physiological information, so replacing reliance upon auditory alarms and visual displays with continuous auditory information (Fitch and Kramer, 1994; Loeb and Fitch, 2002; Seagull et al., 2001; Watson et al., 2000a; Watson and Sanderson, 2004). If an effective sonification of key physiological parameters could be developed, the operator's dependence on threshold alarms might be reduced. In a 'what if?' analysis of our observational data, we calculated the expected reduction in alarm noise if the five key physiological parameters were sonified rather than having upper and lower limit threshold alarms (Watson et al., 2000a). With a sonification of heart rate, oxygenation, respiration rate, tidal volume and end tidal carbon dioxide, the total number of auditory alarm soundings would be reduced by 48% from the previous number and the total number of alarm limits breached would be reduced by 63% (see the Venn diagram on the right in Fig. 1). Experimental results to date with anaesthetist participants using pulse oximetry plus a respiratory sonification prototype suggest that continuous information displayed through sonification supports an awareness of the status of physiological parameters that is approximately equivalent to the level of awareness with visual displays. With sonification, however, participants show a greater ability to perform other tasks and exhibit much lower physical workload (Watson and Sanderson, 2004; Sanderson et al., 2004).

Of course, these results do not represent what would happen with an extended physiological sonification in the operating theatre, since many other aspects of the information environment would change in reaction to such a display. Moreover, although sonification appears promising, we still need to be cautious. For example, continuous availability of information could possibly create hypervigilance if a sonification does not appropriately discriminate normal and abnormal states and if it does not function preattentively, as Woods (1995) recommended. Simulator and clinical trials are needed before any design solutions are adopted.

4.2. Discrete auditory displays

In principle, if key patient status information were clearly encoded into sonifications, then anaesthetists could maintain a situation awareness close to one that could otherwise be obtained by continuously looking at the visual displays. Moreover, as more patient information is provided in auditory displays, then any reliance upon auditory alarms for state information might lessen. In this section we explore the possibility of sonifying a further parameter—blood pressure.

If blood pressure were to be sonified, as several authors have suggested (Fitch and Kramer, 1994; Loeb and Fitch, 2002; Seagull et al., 2001), then the information required by the anaesthetist in the blood pressure example from our field study could be available without the work required to continually adjust the alarms.

In the hypothetical case shown in Fig. 7, the patient's blood pressure is high, as is indicated by a change in the sonification sound dimension representing blood pressure and a correlated change in end tidal carbon dioxide (callout 1). If a blood pressure sonification were well designed the anaesthetist could judge if the systolic blood pressure is approaching normality at the expected rate (callout 2a). A change in the sound dimension representing blood pressure focuses the anaesthetist's attention on the rate of change in blood pressure, removing the requirement to tailor the auditory alarms (callout 2b). If changes in the sonification that the anaesthetist hears are not sufficient to diagnose the patient's state, then the change in itself may direct the anaesthetist's attention to the visual display to read the systolic blood pressure directly (callout 3). The visual display can then be used to confirm the rate of change of the patient's systolic blood pressure (callout 4). In the sonification, the sound dimension representing blood pressure acts as a task scheduling interrupt, which reduces the need for the anaesthetist to remember to check the visual display, so decreasing the anaesthetist's workload (callout 5). In contrast to alarms, a change in the sonification will act as an interrupt at the precise moment that the blood pressure change or when something unexpected occurs to the patient. Expected changes in the patient state will have corresponding expected changes in the sonification and will therefore not require an unduly high level of monitoring.

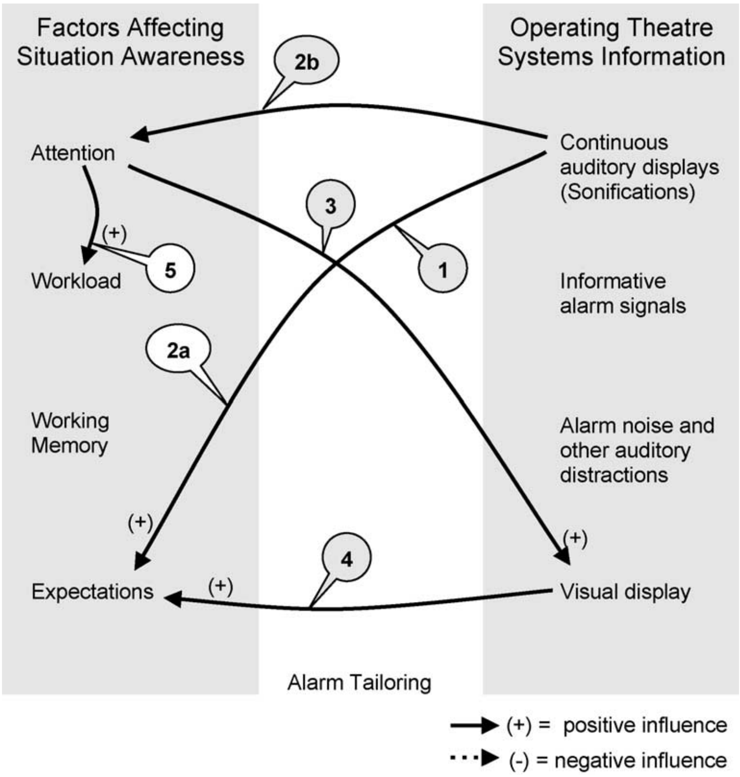

Fig. 7. Influence diagram of hypothetical case of handling high blood pressure with a sonification.

Although sonification may provide a solution that would support anaesthetists in many situations in which they currently wish to tailor their equipment, there are arguments that sometimes discrete auditory displays may be more appropriate. Since not all information is measured continuously, a sonification may contain incorrect information between successive measurements of a parameter. We use blood pressure to illustrate the potential danger of such a design.

In many operations arterial blood pressure is not measured continuously and anaesthetists rely on intermittent NIBP measures (Webb et al., 1993). A sonification of arterial blood pressure would be a valid representation of the patient's blood pressure from moment to moment. In the blood pressure example provided earlier, however, an NIBP measuring device gave a new blood pressure measurement only every 2 min. If NIBP information were to be presented continuously then the sonification may contain incorrect information (see Fig. 8). Changes in other parameters are often correlated with blood pressure; for example, end tidal carbon dioxide will drop when blood pressure drops because of a low cardiac output. Continuous representation could reduce anaesthetists' situation awareness as they may base hypotheses on blood pressure information that was measured minutes ago and may now be irrelevant.

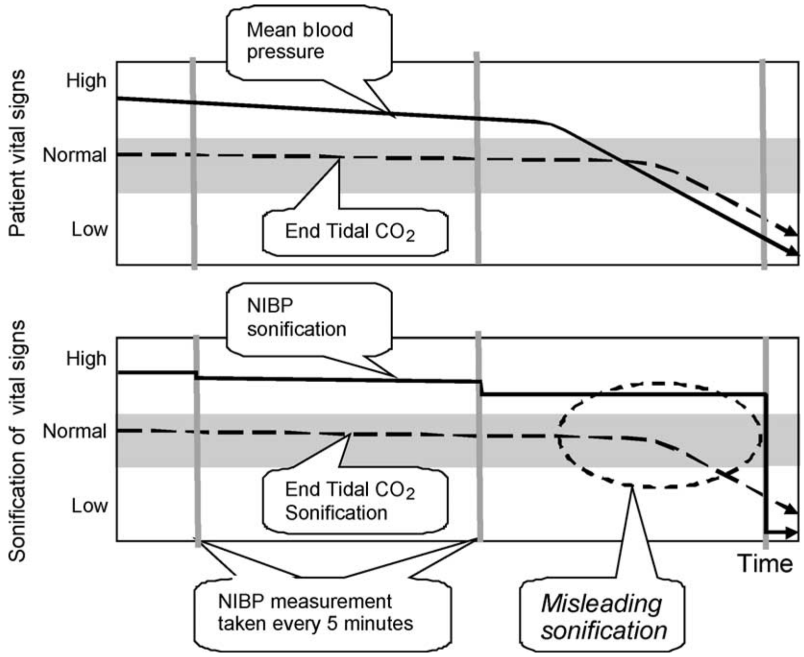

Fig. 8. Map of measured physiological measurements against actual physiological values showing how incorrect information included in sonification could lead to incorrect conclusions.

Other authors have suggested using informative displays such as auditory icons and earcons to represent lower or higher level patient information (Woods, 1995). Earcons are auditory displays that encode data or system states into short tunes (Blattner et al., 1989) whereas auditory icons are sounds that have immediate natural associations with a state or object (Gaver, 1986). Unlike sonifications, auditory icons and earcons still require the listeners' focal attention after they are presented in order to interpret what they mean (Graham, 1999; Leung et al., 1997). A balance between different auditory displays and the flexibility within the system for tailoring may provide the appropriate combination to keep anaesthetists continually aware of the patient's state without unnecessarily increasing their workload.

An influence diagram shows that an NIBP earcon designed with the intention of identifying the source of the information and providing information about the systolic and diastolic pressure could be combined with sonifications of continuously measured parameters. In Fig. 9, the patient's blood pressure becomes high, indicated by a change in the earcon sound (callout 1a). After treatment, if there is a sudden vasodilation and drop in cardiac output, this may be detected indirectly by changes in the sonification for $ETCO_2$ (callout 1b). When the NIBP changes from the previous level, the earcon could attract the anaesthetist's attention to a change in the systolic blood pressure (callout 2a). If changes heard by the anaesthetist in the sonification are not sufficient to diagnose the patient's

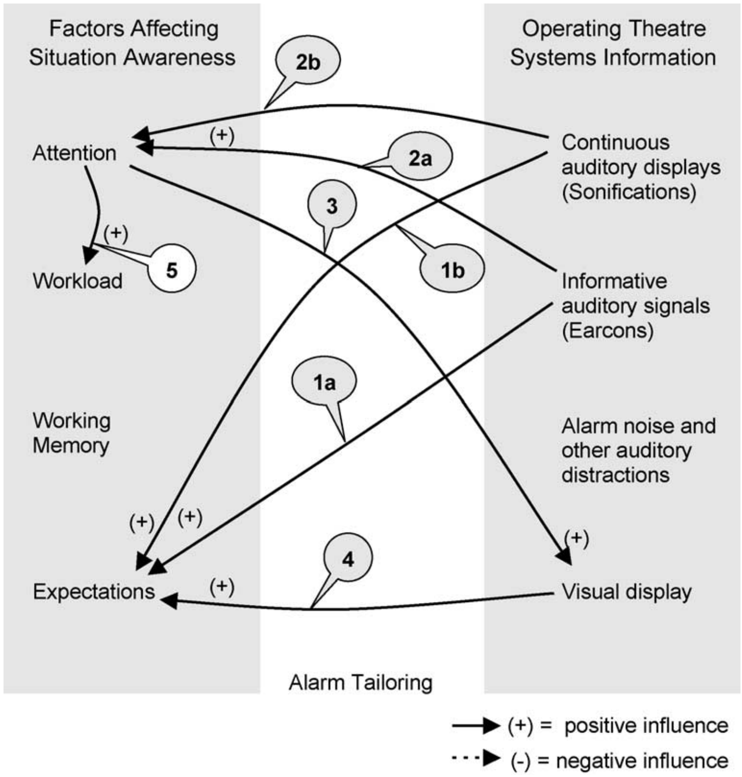

Fig. 9. Influence diagram showing how incorrect information included in sonification could lead to incorrect conclusions.

state then the change heard will direct the anaesthetist's attention to the visual display (callout 2b) and 3. If the anaesthetist is in doubt about what the earcon and sonification are together indicating, then both the earcon and sonification act as a reminder to look at the visual display for the rate of change in the systolic blood pressure (callout 3). The visual display can be used to confirm the rate of change of the patient's systolic blood pressure and the time of the last measurement. The change in the NIBP earcon may act as a task scheduling interrupt, reducing the need for the anaesthetist to remember to check the visual display (callout 4). Because the anaesthetist may become used to the NIBP earcon occurring at regular intervals, the earcon may not interrupt working memory as much as an unexpected alarm (callout 5).

Whether earcons can effectively give anaesthetists the information they need has not yet been evaluated. However, the influence diagram illustrates the potential advantage of an earcon over alarm tailoring to obtain the same information (Fig. 9). The advantage of the earcon over tailoring will depend upon how effectively anaesthetists could identify the information they need from an earcon in the operating theatre while conducting other tasks.

5. Conclusions

In summary, end-users may see the benefits of tailoring their systems, whether tailoring is actually performed will depend on a series of factors, some promoting tailoring and others inhibiting tailoring. The key requirements that emerge from our field observations and analyses of anaesthetists' activities are that attention needs to be released from visual monitoring for other tasks, but that attention should remain capable of being captured by unusual patient states. Tailoring can actually reveal information requirements. Rather than providing better ways for users to tailor alarm systems to achieve this goal, designers might instead provide auditory displays of patient states to deliver the appropriate support for attention. The results of preliminary studies from our laboratory suggest that a respiratory sonification design (Watson and Sanderson, 2004; Watson et al., 2003; Sanderson et al., 2004) and a blood pressure earcon design (Gill, 2003) effectively convey information to listeners.

Our influence diagrams let us describe the actual or possible impact of auditory displays in the context of real-time problem solving. The influence diagrams can also indicate further studies to test our ideas. We have already started investigating how a respiratory sonification will be affected by background noise and alarms (Shek, 2003). Future experiments will examine the effects of the respiratory sonification on anaesthetists' expectations and will examine the impact on training, expertise and team coordination.

Many researchers have emphasized that tailoring can help users compensate adaptively for the inevitable lack of fit between the system as designed and the system as operated (Rasmussen et al., 1994; Mumaw et al., 2000). Other researchers emphasize that tailoring has disadvantages, viewing it as a possibly risky compensation for fundamentally inadequate design (Cook and Woods, 1996). For us, alarm tailoring provides evidence about how users wish to manage their attention, which has design consequences. The general form of our recommendations may not, however, transfer directly to other domains. For example, the use of alarms and the need to tailor alarms in intensive care units is likely to work differently from the operating theatre. We have argued that any system requiring tailoring will lead to better performance only if there is time to tailor, the means are there, and the benefits appear to outweigh the costs. Overall, designers should assess whether any end-user tailoring observed in existing systems actually indicates the need for a revolutionary change in the way information is delivered and acted upon.

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