Designing for Attention With Sound: Challenges and Extensions to Ecological Interface Design

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Objective: We explore whether ecological interface design (EID) principles can be applied to the design of an auditory display for anesthesia monitoring. **Background:** EID examples focus almost exclusively on visual displays. In the anesthesia work environment, however, auditory displays may provide better individual and team awareness of patient state. **Method:** Using a work domain analysis of physiological monitoring in anesthesia, we identify information to display. Using the skills, rules, and knowledge distinction we identify cognitive control needed. Using semantic mapping we map physiological variables and constraints to auditory dimensions. **Results:** EID principles do not address when information should be displayed and to whom. An attentional mapping stage helps to specify answers to these questions so that a workable auditory display for anesthesia monitoring is achieved. **Conclusion:** EID principles of representing work domain functional structure and minimizing resource-demanding cognitive control are necessary but insufficient to specify requirements for an effective auditory display. Also needed are analyses of control tasks, strategies, and the social organization of work. Such analyses are an integral part of the broader cognitive work analysis framework from which EID emerged. **Application:** Actual or potential uses of this research include the design of displays that support continuous peripheral awareness in collaborative multimodal work environments.

INTRODUCTION

Over the past two decades, the analysis, modeling, design, and evaluation of complex sociotechnical systems has tended to focus on the role of visual displays in promoting effective human-system integration. There is much less research on the design of displays in other modalities, such as auditory or haptic displays. In this paper we extend ecological interface design (EID; Burns & Hajdukiewicz, 2004; Vicente, 2002) to the design of an auditory display. Although researchers have explored auditory displays for process monitoring (Fitch & Kramer, 1994; Gaver, Smith, & O'Shea, 1991; Johannsen, 2004; Rauterberg, 1997) and have adopted ecological approaches to understanding auditory perception (Gaver, 1993), auditory display design (Walker & Kramer, 2004), and alarm design (Stanton & Edworthy, 1999), there has been relatively little discussion of extending EID to the design of auditory displays.

Working within the anesthesia domain, we use EID to develop a *sonification* to supplement conventional visual displays (Kramer, 1994). Sonifications are continuous auditory displays that code data into perceived relationships in sound (Barrass & Kramer, 1999; Kramer, 1994) – an example is the Geiger counter. As we developed a potentially viable sonification to support respiratory monitoring (Watson & Sanderson, 2004), we found areas in which EID does not provide explicit principles for guiding the design of auditory displays and may need to be extended.

In the remainder of this section we describe EID and highlight aspects of design that EID has not explicitly addressed. In the next section we identify monitoring challenges that anesthesiologists face and discuss how current visual and auditory displays may leave some needs unfilled. In the third section we analyze anesthesiologists' information needs, guided by EID. We identify design issues not explicitly addressed in EID principles

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(Vicente, 2002; Vicente & Rasmussen, 1990, 1992) or in guidelines for using EID (Burns & Hajdukiewicz, 2004; Reising & Sanderson, 2002a). In the fourth section we map information needs onto auditory dimensions to produce potential displays. In the fifth section, we briefly report an evaluation of the final display. Our steps through these issues are shown in Figure 1. Finally, we reflect on implications of our findings for extending EID to auditory displays.

Ecological Interface Design and the Auditory Modality

We briefly outline cognitive work analysis because EID and our discussion of extending EID

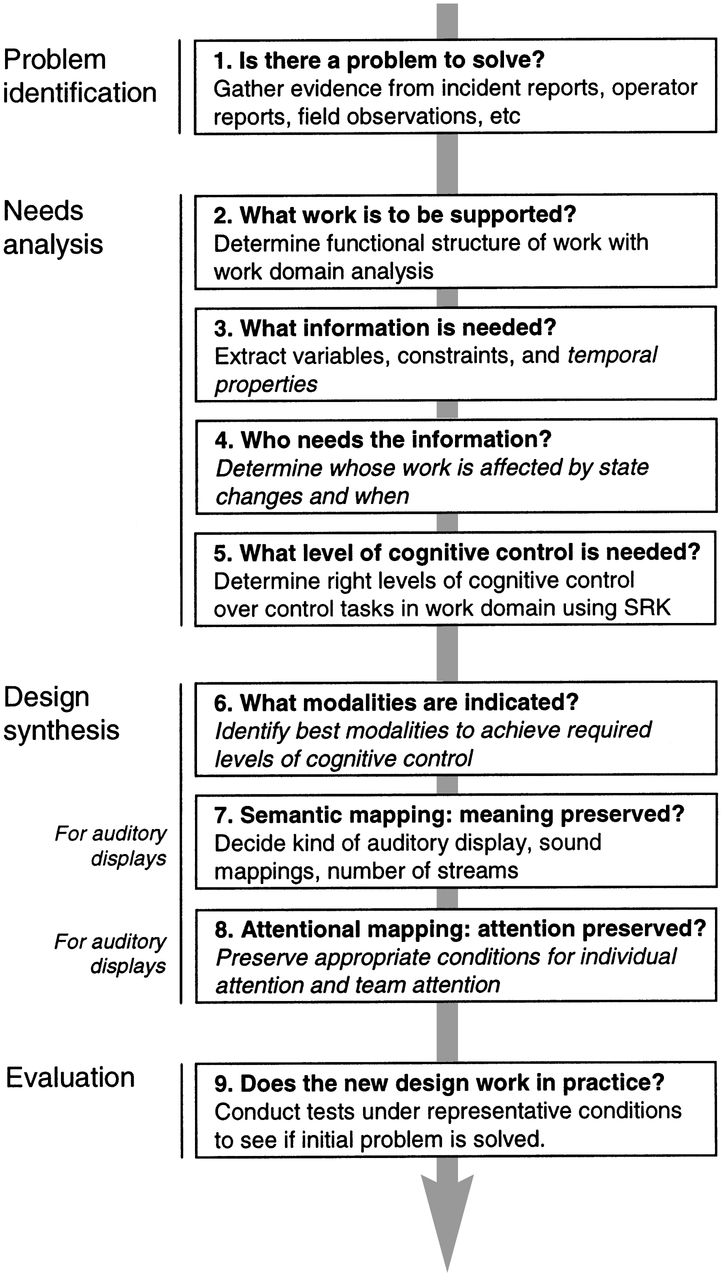

Figure 1. Process for the design of auditory displays using EID. Parts in italics represent aspects not typically considered in EID. SRK = skill-, rule-, and knowledge-based behavior.

draw upon it. Cognitive work analysis is a framework that helps analysts identify constraints that shape the activity of people at work (Rasmussen, Pejtersen, & Goodstein, 1994; Vicente, 1999). The constraints are (a) the structure of the work domain itself, (b) control tasks that must be undertaken, (c) the range of possible strategies for undertaking the control tasks, (d) the social organization of work, and (e) cognitive competencies of workers, such as skill-, rule-, and knowledge-based behavior. These constraints are represented in five phases of analysis. EID draws upon the work domain analysis and worker competencies analysis phases.

Three principles underlie EID (Vicente, 2002; Vicente & Rasmussen, 1990, 1992). First, interface content should support knowledge-based behavior by reflecting the functional structure and inherent constraints of the work domain. Second, interface content should support rule-based behavior by mapping perceptual forms directly into work domain constraints. Third, the interface should support skill-based behavior by allowing direct manipulation of system elements. A systematic design process helps the designer present work domain functional structure and constraints so that less intensive mental processing is needed (Burns & Hajdukiewicz, 2004).

EID researchers have focused on visual displays and are only just starting to consider auditory displays. However, visual and auditory displays have different affordances, or possibilities for interaction. First, when played through speakers, auditory displays can be heard regardless of a listener's posture – they have a *ubiquitous* rather than *localized* property. Second, auditory displays will be heard by anyone nearby, regardless of intent – they have an *obligatory* property (i.e., they always reach the sensorium) rather than an *optional* property. Third, auditory displays occur in time and cannot be reviewed at will by reorienting one's sense organs – they have a *transitory* rather than a *persistent* property.

Developed primarily for visual displays, EID principles may need further development to meet requirements affected by those affordances (Sanderson, Anderson, & Watson, 2000). First, EID does not provide explicit principles for balancing the needs of teams versus individuals. Because visual displays are optional, only the person who needs the information needs to look, whereas because auditory displays are obligatory, they are heard but may not help others' cognitive work. Second, EID does not explicitly specify how a display might recapture attention. It is assumed that visual displays will be attended to when needed, despite being localized. However, auditory displays may draw attention when not needed, given their ubiquitous and obligatory properties. Third, EID does not provide explicit principles for handling the transitory nature of most auditory displays. Because visual displays are persistent, it is assumed they will be available when needed.

Therefore we must consider not only whether auditory displays convey the right information in a compelling format but also how and when they will guide attention and who will have to hear them. The design of auditory displays under an ecological approach will involve a *semantic mapping* process, just as does the design of visual displays (Bennett & Flach, 1992; Reising & Sanderson, 2002a). We suggest that the design of auditory displays should also involve an *attentional mapping* process (Sanderson et al., 2000) that includes an analysis of whose attention should be manipulated by the auditory display and how the auditory display should guide attention to important properties. In the next sections we describe how this conclusion emerged from our attempts to develop an auditory display to support respiratory monitoring in anesthesia.

PROBLEM IDENTIFICATION

Field research and incident monitoring data indicated that anesthesiologists might benefit from a ubiquitous and obligatory display of patient information.

Field Studies

Field studies suggest that anesthesiologists may benefit from receiving patient information continuously but unobtrusively (Cook & Woods, 1996; Seagull & Sanderson, 2001; Watson, Sanderson, & Russell, 2004). Anesthesiologists wish to know about changes in the patient's status as soon as possible so they can take corrective action, because patients who do not receive adequate oxygen can suffer irreversible brain damage within 4 to 6 min. Anesthesiologists sometimes "tailor" their alarm systems to give them continuous information about the patient's state, but without having to continually hear alarms or watch displays (see Watson et al., 2004). Auditory interfaces that provide critical information continuously by making displays ubiquitous and obligatory without extra workload could be useful supplements to visual displays.

Incident Report Data

Incident report data suggest that an integrated and continuous display of patient vital signs may speed detection of events that could lead to adverse outcomes. Pulse oximetry is a sonification of the patient's arterial oxygen saturation (SpO_2) and heart rate (HR), usually measured from a small finger-clip sensor. The rate of a series of beeps indicates the patient's heart rate, and the pitch of the beeps indicates oxygen saturation. Reports in the Australian Incident Monitoring Study (AIMS) show that pulse oximetry initially indicated a problem in 27% of reported events, which accounts for more detections than any other monitor. This is possibly because of its continuous audible tone (Webb et al., 1993). Second to pulse oximetry, *capnography* detected 24% of reported events. Capnography measures the amount of carbon dioxide in the gas coming out of the lungs on expiration, or end-tidal carbon dioxide ($ETCO_2$), which provides an estimate of arterial carbon dioxide values. However, capnography has only a visual display.

Taken together, the measurements of HR, SpO_2, respiration rate (RR), the volume of gas going in and out of the lungs (tidal volume or V_T), and $ETCO_2$ contributed to the detection of over 90% of evolving incidents in the AIMS study (Runciman, Webb, Barker, & Currie, 1993). These findings have been supported in closed claim reports (Tinker, Dull, Caplan, & Cheney, 1989) and in more recent incident report summaries (Cote, Notterman, Karl, Weinberg, & McCloskey, 2000; Findlay, Spittal, & Radcliffe, 1998; James, 2003). A display of respiratory vital signs in a continuous format compatible with pulse oximetry could therefore help the anesthesiologist achieve an overview of the most important aspects of a patient's physiological state.

NEEDS ANALYSIS

We turned to EID to provide a more complete analysis of anesthesiologists' information needs because it is suited to complex safety-critical domains and identifies information humans need to handle unexpected events. Our needs analysis encompasses Steps 2 through 5 of Figure 1 and includes work domain analysis (WDA) and a consideration of how to move monitoring to lower levels of cognitive control. We also analyzed the temporal properties of the work domain to prioritize information the anesthesiologist needs, and we considered who needs patient information.

Work Domain Analysis

WDA produces a representation of the purposes, first principles, functions, processes, and configuration of any work domain in which a human agent is responsible for handling disturbances and maintaining desired operation (Rasmussen et al., 1994; Vicente, 1999; see Step 2 of Figure 1). WDA helps to specify the information the human operator must have in order to carry out these roles effectively.

Our WDA of the physiology of a patient undergoing anesthesia was developed in five stages:

1. Initial field observations and discussions with subject matter experts (SMEs) about the information that operating room (OR) staff used to infer higher order patient states.
2. A review of medical texts such as Guyton and Hall (1996) and Miller (1994) for formal models of the relationship between sensed values and higher order states.
3. The development of an initial WDA of the domain.
4. A second round of field observations focused on anesthesiologists' responses to alarms.
5. A review of a revised WDA with a senior consultant anesthesiologist holding a doctorate in physiology and with a second SME holding qualifications in clinical physiology.

The fullest version of the WDA included the entire surgical situation, with the roles of the surgeon, anesthesiologist, and patient represented as separate subdomains (Watson & Sanderson, 1998; see also work by Hajdukiewicz, Vicente, Doyle, Milgrim, & Burns, 2001). For example, the anesthesiologist manages major side effects of surgery (pain, awareness, movement), manages the patient's coexisting diseases, and maintains and supports homeostatic control of oxygenation, ventilation, and perfusion to core organ systems (Miller, 1994). We then focused on information about the patient's physiology that the anesthesiologist needs to monitor. The human body was modeled for a resting state over the approximate time period that a patient might be under anesthetic (15 min–20 hr). The WDA identified key vital signs and relationships relevant for recognizing physiological changes in the human body at rest.

Figure 2 is a summary of a much larger abstraction hierarchy representation of the work domain that is impractical to show here (see Watson, 2002).

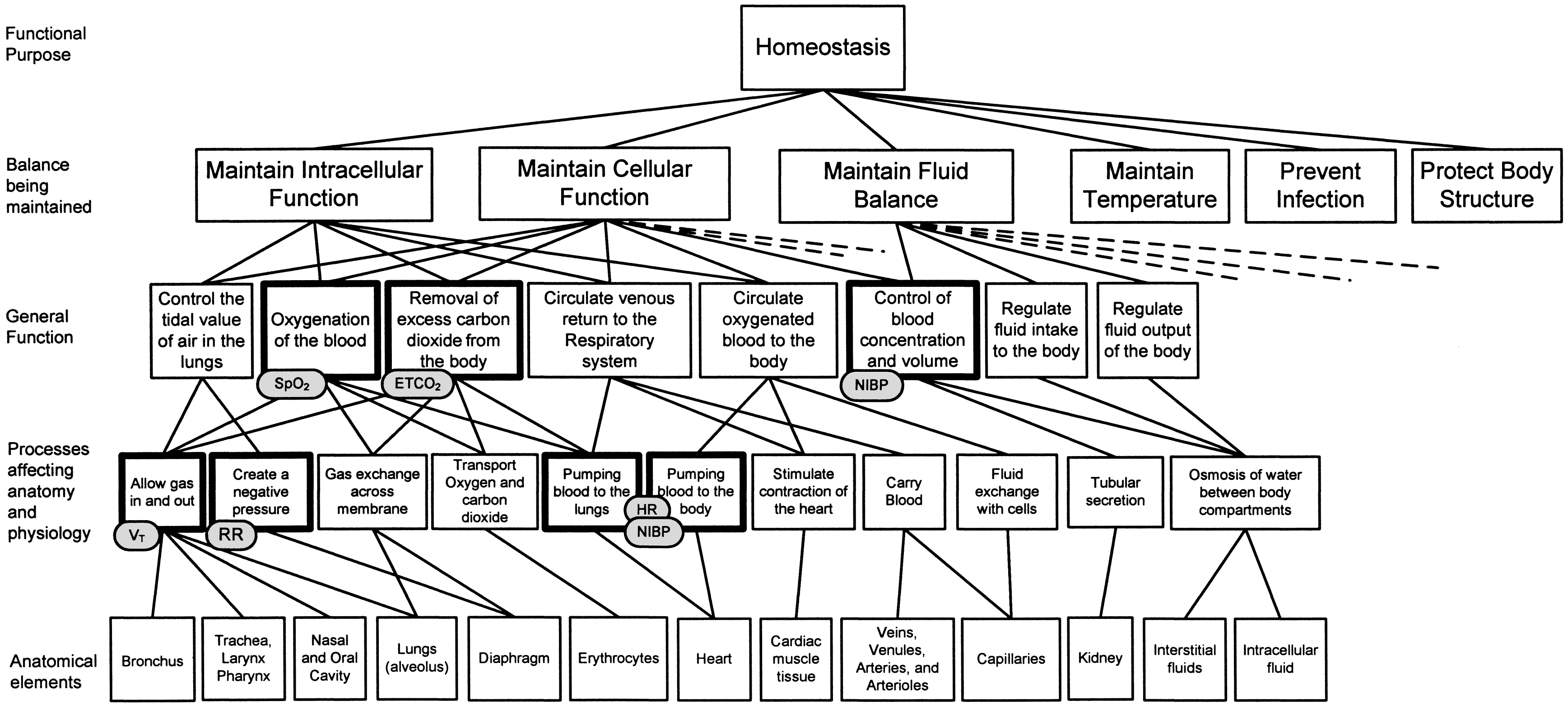

Figure 2. Select elements from the WDA for the human body at rest, indicating measurable vital signs that may be appropriate for a sonification of patient physiology. Small nodes are sensing points.

The functions and processes that support the overall functional purposes of homeostasis were identified. The abstract function level represents balances being maintained to achieve homeostasis. The general functions level represents processes such as circulation and oxygenation that can each be represented by a complex functional model, even while all are interdependent. The physical functions are physiological processes specific to particular physical forms, and physical forms are where anatomy is modeled at the gross and cellular levels.

The relationship between patient monitoring equipment and the patient's physiological functions and processes was used to describe the information that anesthesiologists obtained from each monitor (Watson, 2002). For example, when focusing on pulse oximetry, we could identify how information about oxygen saturation of the blood contributes to the anesthesiologist's awareness of the patient's extracellular and intracellular functions (see Figure 2).

Sensed and Derived Values

Researchers using EID usually seek to display information about functional purpose and abstract functions so that humans can monitor the stability of such high-level properties. Unfortunately, no sensors exist that provide direct information about how well abstract functions such as extracellular or intracellular functions are being maintained or about many of the physiological processes supporting those functions (Gravenstein, 1998).

In other domains, EID researchers have used models of the first principles of the work domain to derive higher order properties from the sensed values and then to display the derived properties directly (Reising & Sanderson, 2002a; Vicente, 2002). In the OR, however, sensors are not as stable or as formally verified and validated as they are in process control. Clinicians must continually distinguish sensor abnormalities from physiological abnormalities, integrate the results, and allow for small or large idiosyncrasies in patient response (Gravenstein, 1998). To date, all visual interfaces showing higher order properties have used simulated patient models (Blike, Surgenor, Whalen, & Jensen, 2000; Jungk, Thull, Hoeft, & Rau, 1999) in which reliability is not a problem. Until these difficulties are resolved, lower order data can be displayed in a way that helps higher order properties emerge configurally, so that clinicians can infer extracellular and intracellular function while allowing for unreliability (see Wachter et al., 2003).

Temporal Relations

To prioritize vital signs for displays we considered the time frame of potential changes and their criticality (see addition of *temporal relations* in Step 3, Figure 1). The analysis of temporal relations is not an explicit part of EID, and WDA does not readily capture temporal relations. Capturing temporal relations visually has not been a key concern of EID (but see Bennett, Payne & Walters, 2005; Hansen, 1995). However, understanding temporal relations is important when mapping the dynamic properties of a process into the temporal properties of auditory displays.

Different physiological functions (abstract functions) may be addressed by OR staff across different time frames. Maintaining body structure and preventing infection are usually managed over long time frames and are monitored intermittently rather than frequently. Given current sensing technology, they need not be considered for a real-time OR display. Fluid balance and temperature usually take longer than most other properties to reach abnormal range, but because they can be of immediate concern to OR staff they might require some form of auditory display to direct attention to abnormalities. Maintaining extracellular and intracellular functions, however, has implications for the body well within the time frame of any OR procedure, so this became our main area of focus. As Figure 2 shows, HR, SpO_2, RR, V_T, and $ETCO_2$ provide information about the four processes in the general function level of the abstraction hierarchy, which, in turn, can provide information on extracellular and intracellular balances. Blood pressure can also provide information about extracellular function and can help the clinician detect rapid fluid loss. However, because most operations still use noninvasive blood pressure (NIBP) cuffs, which update information only every few minutes, blood pressure (BP) was left for a separate design effort (see Watson & Gill, 2004, and Watson et al., 2004, for further details).

Recipients of Information

Patient monitoring is at times a vigilance task, and vigilance is sustained better – and with a lower level of subjective stress and workload – with auditory rather than visual displays (Szalma et al., 2004). However, the fullest version of our WDA indicates that the anesthesiologist works in a team that may include senior or junior colleagues plus anesthesia nurses and technicians. The OR is shared with the surgical team, where the surgeon may be accompanied by a senior or junior colleague, an assistant, nursing staff, and other specialists. Who should receive information, when, and how are therefore important considerations (see Step 4 of Figure 1), but EID principles do not explicitly address this.

If a patient becomes unstable, team members must coordinate to handle the situation and to predict imminent needs, given the patient's state (Helmreich & Schaefer, 1994). Awareness of other team members' work, particularly through the auditory modality while attending to one's own work, can improve collaboration (Heath & Luff, 1992; Patterson, Watts-Perotti, & Woods, 1999; Surgenor, Blike, & Corwin, 2003).

With its ubiquitous and obligatory property, an auditory display could be useful during specific phases of work in the OR, such as managing team collaboration during high-tempo work periods or sustaining an individual anesthesiologist's vigilance during low workload. How the presentation of patient information can transition from being ubiquitous and obligatory to being localized and optional, as needed, should be addressed during design. Considering recipients and their auditory needs is crucial if a display is to support different modes of team work effectively.

Identifying Required Cognitive Control

In our fieldwork we noticed a mismatch between the kind of cognitive control (skill-, rule-, or knowledge-based behavior) available to the anesthesiologists, given the monitoring equipment and the kind of cognitive control they sometimes preferred. EID guides researchers to display information so that (a) the efficiency and effectiveness of skill-based behavior are supported, (b) the human can step through rule-based behavior when routine recognition is needed, and (c) the human can engage in knowledge-based behavior when unexpected situations occur (Burns & Hajdukiewicz, 2004; Vicente, 2002). The kind of cognitive control needed may vary in different kinds of procedures and at different points in a procedure (see Step 5 of Figure 1); (Seagull & Sanderson, 2001). We hypothesized that a change in display *modality* rather than a change in visual layout or greater ability to customize the interface might change the way cognitive control is exercised.

First, maintaining awareness of the patient's state should be a skill-based activity based on space-time signals, but visual monitors can make maintaining awareness a rule-based activity, prone to error. Anesthesiologists' tailoring of their work space is partly motivated by this problem. The AIMS study data suggested that variable-tone pulse oximetry – a ubiquitous, obligatory display – helped anesthesiologists detect events early and with a low level of cognitive control (Webb et al., 1993). The same advantage could extend to other variables.

Second, auditory alarms often recapture attention, and responding to them is faster than to visual alarms (Morris & Montano, 1996). However, they cause distraction, and their uninformative nature leaves the appropriate level of response unclear: Should it be a skill-based response such as silencing, a rule-based assessment taking the information at face value, or a knowledge-based assessment questioning the face value of the information? Continuous auditory displays could prevent distraction while supporting an appropriate level of cognitive control.

Summary of Needs

The AIMS study (Webb et al., 1993) and analyses performed on our field data (Watson et al., 2004) indicate that five sensed vital signs are important for continuously monitoring a patient's physiological processes during anesthesia. A WDA indicated that preserving extracellular and intracellular functions is critical within the time frame of anesthesia and that the five vital signs together would provide information about those functions. Considerations not normally part of EID are shown in italics in Figure 1. They include the analysis of temporal properties of vital signs (Step 3, Figure 1), consideration of who should get the information and when (Step 4, Figure 1).

DESIGN SYNTHESIS

In this section we outline how we moved from the analysis of needs to specific auditory display designs (see Figure 1, Steps 6–8).

Establishing a Modality

It is important to consider whether the level of cognitive control might be influenced by introducing a second modality (Step 6, Figure 1). Not every analysis of needs will point to a specific modality as strongly as ours did. The role of pulse oximetry in mitigating incidents and the role of auditory information in coordinating team activity, sustaining vigilance, and translating control to the skill-based level all indicated the possible benefits of an auditory display. As discussed, sonification can potentially support skill-, rule-, and knowledge-based behavior. Compared with visual displays, however, sonification may be most suited to supporting skill-based behavior because of its inherently transitory nature. Johannsen (2004) has suggested that designers should develop auditory displays principally to minimize human error at the skill-based level.

Our findings and the foregoing arguments are consistent with research showing that auditory displays can support people's peripheral awareness of system state while they perform other tasks (Gaver, 1997; Kramer, 1994; Neuhoff, Kramer, & Wayand, 2002; Rauterberg, 1997; Sarter, 2000; Woods, 1995). Sonification therefore should support skill-based behavior on its own but should still let anesthesiologists integrate information from both the auditory and visual modalities when engaged in rule- and knowledge-based reasoning. Some other display formats were possible, such as head-mounted displays (Sanderson, Watson, & Russell, 2005; Via, Kyle, Geiger, & Mongan, 2002) and intelligent alarms (Mylrea, Orr, & Westenskow, 1993; Oberli et al., 1999), but were rejected. They either introduced problems, such as the possibility of inattentional blindness or low trust, or failed to support continuous awareness.

Semantic Mapping

Semantic mapping is the process by which the functional structure and constraints in a work domain are mapped to perceptual forms in a way that supports cognitive control at the desired levels (Bennett & Flach, 1992; Reising & Sanderson, 2002a). There is no established base of knowledge for semantic mapping for auditory displays, although Kramer (1994) and Barrass (1997, 2003) have provided recommendations. For auditory semantic mapping, we consider the information-carrying potential of various auditory dimensions (Sanderson et al., 2000). Here we describe how we arrived at a workable sonification of respiratory vital signs (Step 7, Figure 1).

Kinds of auditory displays. First we determined the most appropriate kind of auditory display given needs identified. As noted, sonifications are continuous auditory displays that map relations in data to relations in auditory dimensions. *Earcons* are "abstract, synthetic tones that can be used in structured combinations to create sound messages to represent parts of an interface" (Brewster, Wright, & Edwards, 1994, p. 471–498), such as a family of sounds for supporting browser navigation. *Auditory icons* are sounds that have direct associations with the event, such as the sound of a closing door when closing a folder on a computer (Gaver, 1986; Kramer, 1994).

Based on the rates of change discussed earlier and the information in our WDA, we mapped information about physiological and anesthetic systems onto the most appropriate kind of auditory display. Critical patient information that changes significantly during an operation should be continuously available and so may be best presented via sonification. Examples are respiratory parameters, continuous BP, level of awareness, and pulse oximetry. Patient information that is slower to change or that needs to be monitored only intermittently may be best presented via earcons. Examples are NIBP, temperature, and level of muscle paralysis. Infrequent signals, and information that if not responded to immediately would harm the patient, may be best presented via auditory icons or alarm interrupts (Fitch & Kramer, 1994). Examples are changes in temperature, paralysis, system pressure, and levels of gas delivered to the patient.

Candidate sound dimension mappings. Once the kind of auditory display is established, the properties of measures (e.g., vital signs) must be mapped to properties of sound that preserve the measure's most important characteristic and that indicate when functional boundaries are near. The third column in Table 1 classifies vital signs according to whether their measurement involves a complex transduction process leading to an abstract quantity. The fourth column notes how the output of each vital sign is sensed and presented over time: cyclically for HR and RR; continuously within those cycles for SpO_2, ABP, and $ETCO_2$; or intermittently (and at arbitrarily defined intervals) for NIBP. The last column identifies dimensions of sound such as tempo, duration, and various tonal qualities that map naturally to the output characteristics of the vital signs. These dimensions could carry the information represented by each vital sign.

TABLE 1: Properties of Representative Vital Signs and Suitable Sound Dimensions for Sonification

		Properties		
Viral Sign	Units of Measure	Abstract Measure	Output	Suitable Sound Dimension(s)
Heart rate (HR)	Beats/min	No	Cyclic	Tempo
Stroke volume	m^3	Yes	Cyclic	Tonal or duration
Oxygen saturation (SpO_2)	mmHg	Yes	Continuous	Tonal
Automatic noninvasive blood pressure (NIBP; systolic and diastolic)	mmHg	Yes	Intermittent	Tonal
Invasive blood pressure (BP; systolic and diastolic)	mmHg	Yes	Continuous	Tonal
Respiration rate (RR)	Breaths/min	No	Cyclic	Tempo
Inspiration time (I)	I:E ratio	No	Cyclic	Duration
Expiration time (E)	I:E ratio	No	Cyclic	Duration
Tidal flow (V_{flow}; inspiratory or expiratory)	ml/s	Yes	Cyclic	Δ Tonal qualities
Tidal volume (V_T)	ml	Yes	Cyclic	Tonal
End-tidal carbon dioxide ($ETCO_2$)	mmHg	Yes	Continuous	Tonal
Airway pressure	cm H_2O	Yes	Cyclic	Tonal

Note. "Tonal" sound dimensions mean changes in pitch, brightness, timbre, amplitude, resonance, reverberation, vibrato, or tremolo of a tone.

Number of auditory streams. An important consideration is the number of auditory streams to use (Bregman, 1990). An auditory stream is a sound, or a series of sounds, that forms a coherent series as if it comes from a single source. Deciding the number of auditory streams is like deciding the number of objects that will carry information in a visual display. Although all five vital signs could conceivably be combined into one sound stream (Anderson, Sanderson, & Norris, 2002), this would mean changing the "industry standard" pulse oximetry sound. Instead, we maintained the physiological realism of two cyclic processes, one based on cyclic sound pulses representing HR and the other on cyclic sound pulses representing RR. This led to two auditory streams, the first equivalent to pulse oximetry and the second a new respiratory stream.

Promoting skill-based behavior. Skill-based behavior is promoted when a display reflects existing space-time signals or creates new space-time signals that encourage interaction in the same terms. Accordingly, we wished to preserve space-time signals for respiration as much as possible. The depth of anesthesia and level of mechanical assistance from a ventilator both influence RR and V_T and, therefore, the rate at which the patient's chest moves and how high it rises. When a patient's chest rises with an in breath (inspiration) or falls with an out breath (expiration), the rise and fall can be mapped onto a sound dimension so that anesthesiologists can correlate what they hear with what they see. We used cumulative V_T on inspiration and expiration as the variable carrying the base sound for the sonification. V_{flow} then emerges as the rate of change of cumulative V_T over time, and V_T is the final value that cumulative V_T reaches.

Mapping HR and RR to the tempo of separate sound streams preserves the cyclic properties of each vital sign, but neither masks the other. RR emerges from the relative duration of inspiration and expiration, giving the respiratory sonification stream a different tempo from HR but also letting it represent different inspired:expired (I:E) ratios and certain kinds of uneven breathing. High-level properties, such as the minute volume of gas sent to the patient and resistance to mechanical ventilation, may also become apparent. Table 2 shows that the ranges used for the different sound dimensions were sufficiently distinct for auditory stream segregation.

TABLE 2: Sound Dimensions and Values Used to Map Vital Signs

Vital signs	Sound Dimension Used	Range Used
	Pulse Oximetry (and Further Cardiac)	
Heart rate (HR)	Tempo of sound pulses	40–200 beats/min, fixed length
Oxygenation (SpO_2)	Frequency of sound pulse	174–660 Hz
	Respiratory Sonification	
Respiration rate (RR)	Tempo of I:E sound pulse pairs	0–30 breaths/min
End-tidal carbon dioxide ($ETCO_2$)	Frequency of I sound pulse and minor third lower for E sound	150–700 Hz
Inspiration (I)	Duration of I sound pulse	Approx. 1–30 s
Expiration (E)	Duration of E sound pulse	Approx. 1–30 s
Tidal volume (V_T)	Amplitude at maximum V_T for I and E	Variable
Tidal flow (V_{flow})	Rate of change of amplitude of V_T for I or E	Ratio of maximum to minimum widely variable

Note. Ranges chosen are distinct so that sound streams are easily distinguished. Sound dimensions not used in the pulse oximetry stream are held constant. Respiratory sonification is specific to the varying sonification.

Such a mapping could support not only skill-based behavior but also rule- and knowledge-based behavior. First, sonification can signal a deviation from normal. If the breathing tube disconnects from the mask, then the ventilator pumps gas to the room rather than to the patient. Sound volume for V_T rapidly peaks during inhalation and decreases slowly during exhalation. The skill-based response is to reconnect the parts. Second, sonification can act as a sign to follow a rule. If anesthetic is delivered but the ventilator is not turned on, breathing eventually ceases. Sound volume for V_T decreases from breath to breath, and each breath is longer. The rule-based response is to turn on the ventilator. Third, sonification can symbolize an unexpected state. A spontaneously breathing patient may stop breathing, with no movement of chest or abdomen. No sound may be heard. If there is no obstruction and no movement, the skill-based response is to manually ventilate the patient and the knowledge-based response is to consider possible clinical causes.

Choosing the carrier tone. The tone that "carries" each sound stream must have basic spectral characteristics. The breathy, varying, vibrato, even, and short columns of Table 3 include three spectral mappings for the carrier tone of the respiratory sonification in Table 2.

The first carrier tone considered was a breathy tone that mimicked the sound of natural breathing (Fitch & Kramer, 1994; Gaver, 1997; Loeb & Fitch, 2002). Pitch was the center frequency of bandpass-filtered white noise. However, we identified two problems that were confirmed by anesthesiologist collaborators (Watson, Sanderson, & Russell, 2000). First, some properties of the patient's respiration will not be represented in a sonification. For example, some gas delivery systems force a set amount of gas toward the patient. If there is an obstruction that prevents gas reaching the lungs, a gas volume measurement that sounds like a breath could falsely suggest that the patient is still being ventilated. Second, a sound based on natural breathing is more likely to be masked by suctioning, diathermy, conversation, or music than is a spectrally simpler sound.

Because an artificial sound may be less susceptible to those problems, we used a relatively pure tone with a few harmonics to provide a clearly identifiable sound. The first version – the varying tone – was developed with the cumulative volume flow rate for each inspiration and expiration mapped to the amplitude of the respiration sound stream (see Tables 2 and 3). An amplitude change was used to represent cumulative V_T, combined optionally with a timbre change at higher levels. Perception of amplitude alone may be affected by changes in pitch, distance from the source, and ambient noise (Stevens & Guirao, 1962), so the combination of amplitude and timbre was preferred when tested.

Piggybacking information on the carrier tone.

TABLE 3: Considerations Addressed During the Development of the Respiratory Sonification

	Respiratory Sonifications					
Mapping Considerations	Mapping	Breathy	Varying[a]	Vibrato	Even	Short
Spectral properties of the carrier tone	Semantic	Filtered white noise	Tone	Tone with vibrato	Tone	Tone
Audibility against typical OR background noise	(Perceptual)	Poor	Very good	Excellent	Good	Good
Currency of V_T	Semantic and attentional	Yes	Yes	Yes	No	No
Potential to misinterpret sonification for patient breathing	Semantic	Yes	No	No	No	No
Immediate extraction of V_T	Attentional	No	No	No	Yes	No
Continuous availability of V_{flow}	Attentional	Yes	Yes	Yes	No	No
Immediate extraction of RR	Attentional	No	No	No	No	Yes
Immediate extraction of I:E ratio	Attentional	No	No	No	No	Yes
Potential for pitch/volume confusion	Semantic	Nominal	Nominal	Negligible	Minimal	Minimal
Probable level of team tolerance	Attentional (team)	Medium	Medium	Low	Medium	High

[a] Final design choice.

The carrier tone can display further information through other tonal qualities. For example, $ETCO_2$ was mapped as a modulation of the pitch of the carrier tone. High pitch indicated high levels of $ETCO_2$ and low pitch indicated low levels, thus preserving well-documented expectations (Walker, 2002). However, we also needed to distinguish inspiration from expiration. We mapped inspiration pitch to the measured $ETCO_2$ and expiration pitch one musical minor third (three semitones) below the inspiration pitch. We resolved the mapping through reference to physiological functioning, distinguishing by the higher note the effort of the diaphragm involved in inspiration and by the lower note the relaxation of the diaphragm involved in expiration.

Attentional Mapping

In the step we call *attentional mapping* (Sanderson et al., 2000), we attempt to preserve appropriate conditions for individual and team attention (Step 8, Figure 1). Table 3 lists attentional mapping issues and trade-offs across different possible respiratory sonifications.

Individual attention. For sonification, attentional mapping "gives designers requirements for how an auditory display should control attention alongside other interface elements, based in a knowledge of *auditory attention*" (Sanderson et al., 2000, p. 262). With attention controlled through audition rather than vision, strategies for performing control tasks will be affected, as has been found with haptic displays by Sklar and Sarter (1999).

A sonification imposes obligatory and transitory stimuli on an individual (whether delivered via earpiece or speakers), so auditory displays must be designed to control attention properly over time. Attentional mapping involves determining the kind of attention required to remain adequately informed. Seagull, Xiao, Mackenzie, and Wickens (2000) proposed that clinicians use peripheral attention for routine monitoring and goal-state verification and focal attention for problem solving and the interpretation of historical data. An auditory display should support both.

The varying sonification preserved real-time mapping but may have required focal attention over the length of the breath in order to extract V_T from the amplitude at the end of inspiration, RR from the length, and I:E ratio from the ratio of the inspiration and expiration times. To test this we designed an even sonification that played the V_T from the previous breath over the length of the sound, reducing any need to attend to the sonification at a specific time (see Table 3). We also designed a short sonification that compressed the time frame over which the sonification sounded to less than a quarter of the breath length, reducing the need for sustained attention to pick up V_T, RR, or I:E (see Table 3). An empirical test with 12 nonanesthetist participants using simulated patient data revealed that the varying sonification supported the best identification of abnormalities and trends in V_T and $ETCO_2$ and was equal to the short and even sonifications for RR (Watson & Sanderson, 2004).

Attentional mapping should also involve implementing features to make crossing boundary conditions emerge acoustically and attract attention. For example, attention should be directed not to physiological changes within a normal range but, instead, to changes that lead away from a normal range. In the respiratory sonification, we kept the pitch for $ETCO_2$ constant within the normal range of 38 to 42 mmHg but let pitch decrease or increase noticeably once it left that range (Kramer, 1994). Similarly, we used a relatively coarse amplitude change when V_T moved outside the normal range so that clinically significant changes were more likely to attract attention.

Team attention. Attentional mapping for a team gives designers requirements for when and how an auditory display should convey information to one, some, or all members of a team, based on knowledge of auditory communication and the effects of noise on performance (Sanderson et al., 2000). The ubiquitous and obligatory nature of auditory displays means that if they are played over speakers they are usually heard by everyone, so that attentional mapping concerns now extend to the team. Team members must communicate easily, coordinate their activities, and reorient their attention to different information sources as work roles change.

First, an auditory display must be tolerated by everyone who has to hear it (Crocker, 1997; Fidell & Teffeteller, 1981). Highly informative displays are not always the most tolerable displays. For example, we rejected a sonification in which vibrato was used for V_T because it was too penetrating (Table 3). Second, an auditory display must be meaningful for staff who must hear it, helping staff detect abnormal patient states while still performing their normal tasks (Heath & Luff, 1992). Third, if not all staff need to hear a display, then it can be delivered just to those who need to hear it (Patterson et al., 1999) via earpieces and wireless communications. In this way, auditory display becomes localized to the team rather than ubiquitous. Fourth, auditory displays should avoid the speech range so that normal verbal communications are preserved. The top frequencies for the pulse oximetry tone and the respiratory sonification are 660 and 700 Hz, respectively (see Table 2), which is at the lower end of the speech spectrum and away from the most sensitive band around 2000 Hz. Overall, it is important to consider the social organization of a workplace and to examine how a new auditory display might enhance or endanger it.

EVALUATION AND FURTHER NEEDS

Evaluations of auditory displays should sample the context of use in a valid way and should test whether information is conveyed effectively. Evaluations should also be sensitive to ways in which an auditory information system might fail (Step 9, Figure 1), such as failures of cross-modal attention, acoustic interference, and intrusion into others' work.

Results for the respiratory sonification are promising (Watson & Sanderson, 2004), although clinical trials are still needed. In laboratory evaluations we have tested for failures of cross-modal attention by examining patient monitoring performance while concurrent visually presented cognitive tasks are performed. Novices and anesthesiologists perform concurrent tasks better when supported by respiratory sonification than by visual displays, but only anesthesiologists can simultaneously monitor the simulated patient as accurately with the sonification as with a normal visual monitor. After each scenario, anesthesiologists could identify what had happened clinically to the simulated patient equally well with sonification as with visual displays.

The respiratory sonification appears to support skill-based behavior. Participants respond faster to questions about sonified patient status and check visual monitors less often when sonification is available (Sanderson, Crawford, Savill, Watson, & Russell, 2004). Informal observations indicate that when anesthesiologists are distracted with conversation, significant changes in the sonification recapture attention and are immediately recognized as failure in a higher order physiological balance, suggesting that clinical interpretation can be skill based.

Despite these promising results, the effect of sonification on team performance and the effect of anesthesiologists' expectations on their use of sonification are still to be examined in simulators and clinical environments. Moreover, the possible effect of acoustic interference on teamwork should be tested with sonification delivered via earpiece versus speakers as well as for viability with hearing-impaired anesthesiologists (Wallace, Ashman, & Matjasko (1994).

Determining the most appropriate level of abstraction at which to sonify information is complex. EID principles support including information from the abstract function level of the WDA. In the varying respiratory sonification examined here, we did not directly sonify properties and balances such as intracellular function. In contrast to other domains, biomedical instrumentation does not have perfect reliability or redundancy, and the modeling required to derive higher order balances will be only an approximation for each patient. Until such problems are solved, we choose to provide the anesthesiologist with information that, when combined, points reasonably directly to higher order clinical states. However, technologies are emerging that measure higher order properties much more directly and continuously. For example, continuous monitoring of cardiac output – a product of HR and heart stroke volume – is starting to appear. Bispectral index monitoring – an interpretation of electroencephalography that indicates depth of anesthesia – is coming into use, and we are investigating auditory displays for it. EID leads researchers directly to higher order properties, functions, or relations to display and may even indicate where biomedical instrumentation research and development efforts should focus (Reising & Sanderson, 2002b).

CONCLUSION

EID draws explicitly upon two of the five phases of cognitive work analysis – WDA and worker competencies analysis – and has an implicit focus on visual displays. When designing auditory displays, however, one may need to consider additional classes of constraints identified in cognitive work analysis (Rasmussen et al., 1994; Vicente, 1999). Designing a display that lets OR staff work relatively independently under some conditions, but collaboratively under others, involves understanding when work roles shift and different collaborative structures need to be supported (Step 4, Figure 1). This requires analyzing the social organization of work. Designing a display to support continual peripheral awareness while other tasks are performed, but to draw attention effectively when needed, requires analyzing the anesthesia control tasks that must be performed and how they might be structured and combined in time (Step 5, Figure 1). Moreover, constraints on strategies for performing control tasks differ across modalities. For example, the fact that auditory information is ubiquitous and obligatory may reduce the workload associated with monitoring so dramatically, compared with a visual display, that cognitive control moves from being rule based to skill based (Step 6, Figure 1). In addition, auditory information is transitory, and so it represents present states in a very natural way. Past and future states cannot readily be indicated by pointing or gesture and so may become overlooked (Step 8, Figure 1).

The aforementioned constraints need to be analyzed in a way that will feed directly into decisions about display modalities. Differences in the affordances of visual and auditory displays should be specified. Overall, broader design frameworks are needed to help balance the social demands of audition as a ubiquitous modality, the attentional demands of audition as an obligatory modality, and the memory demands of audition as a transitory modality.

In summary, extraordinary advances in visual technologies over the last three decades have led most designers to seek visual support for managing complex systems. However, any visual display is ineffective if an operator does not or cannot look at it when needed, so designers will sometimes need to consider broader aspects of the operator's work to find a way to deliver information effectively. This may involve looking beyond the visual modality for solutions. EID provides a conceptual foundation for this, but all phases of cognitive work analysis probably need to be used if successful displays are to emerge.

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