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The multimodal world of medical monitoring displays

Penelope Sanderson

ARC Key Centre for Human Factors, The University of Queensland, St Lucia, Qld 4072, Australia

Abstract

A vision of the future of intraoperative monitoring for anesthesia is presented—a multimodal world based on advanced sensing capabilities. I explore progress towards this vision, outlining the general nature of the anesthetist's monitoring task and the dangers of attentional capture. Research in attention indicates different kinds of attentional control, such as endogenous and exogenous orienting, which are critical to how awareness of patient state is maintained, but which may work differently across different modalities. Four kinds of medical monitoring displays are surveyed: (1) integrated visual displays, (2) head-mounted displays, (3) advanced auditory displays and (4) auditory alarms. Achievements and challenges in each area are outlined. In future research, we should focus more clearly on identifying anesthetists' information needs and we should develop models of attention in different modalities and across different modalities that are more capable of guiding design.

Keywords: Medical monitoring; Display modalities; Anesthesia

1. A vision of the future

In 2000, the Anesthesia Patient Safety Foundation asked anesthesiologist Matt Weinger to give a "pie in the sky" vision of what the perioperative information management system would be like in the near future. His vision was broad and inclusive. Some of his ideas relate to the kind of information that would be available from new sensor technologies.

> New sensor technologies will measure directly critical system variables to enhance monitoring and decision making. The anesthesiologist will have available real-time continuous plasma drug levels (e.g., propofol, remifentanil, etc.) and levels of relevant endogenous substances (e.g., Glu, K, Na, pH, O_2, CO_2, Hgb, troponin, etc.). A reliable continuous measure of "level of consciousness" based on brain and spinal cord function will be available. New sensor technologies will provide real-time continuous non-invasive measure of organ function at the whole organ (e.g., cardiac output), component (e.g., left ventricular end-diastolic volume), and intracellular (e.g., myocyte [ATP], phosphorylation state of stress activated protein kinase) levels. Clinicians will be particularly interested in monitoring non-invasively energy, electrical state (transmembrane DC potential) and chemical ion (e.g., intracellular calcium or potassium) levels in specific organs (cerebral, cardiac, hepatic, renal, and peripheral tissue). Surgical information systems will be fully integrated with anesthesia information systems to enhance clinical communication and team decision making.

Further ideas related to the mode of delivery of the above information, ranging across visual, auditory, haptic, tactile and olfactory and intelligent support for activity:

> These intelligent control and display systems will be based on years of extensive research and testing. The anesthesiologist will wear a lightweight voice-activated heads-up 3D audio and video display. Although most information will be displayed visually and audibly, other interface modalities (haptic, tactile, and olfactory) will be employed where appropriate. Highly effective decision support systems will utilize artificial intelligence technologies (expert systems, neural networks, genetic algorithms, etc.) to integrate baseline and trended patient information with predictive models based on population data and evidence-based guidelines. Most information will be presented in a "mixed reality" with

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E-mail address: p.sanderson@itee.uq.edu.au.

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> video and computer-generated images over-layed [sic] on the actual clinical view. Haptic interfaces will allow direct control of robotic systems that assist in the conduct of interventional procedures such as direct laryngoscopy. The selective use of automated systems, such as closed-loop control of intravenous drugs (anesthetics, analgesics, neuromuscular blockers, and vasoactive drugs), will be facilitated by ecological interface design (EID) and voice activated supervisory control.

Weinger's vision is informed by his years of experience as a clinical anesthesiologist, and also by his human factors research and development activities (Weinger and Englund, 1990). Weinger is not the only one to have such a vision of the future. In 2004, the American Society of Anesthesiologists (ASA) Newsletter published a series of visions of anesthesia in 2050. Blike (2004), also an anesthesiologist engaged in human factors research and development, provided a vision that focused on context-aware monitoring technology, continuous and non-invasive monitoring of high-level physiological properties, ability to visualize anatomy for procedures, and better usability of devices.

In the few years since Weinger put forward his vision there has been mixed progress. I briefly describe the anesthetist's work and relevant research in attention. Guided by Weinger's vision, I then review some areas of intense current activity on how to deliver patient information to the anesthetist in different modalities. Finally, I draw conclusions about future needs.

1.1. *Anesthesia work*

The high-level goals of the anesthetist are (1) to manage the side-effects of surgery, such as pain, awareness, and movement, (2) to maintain and support the patient's homeostatic control of oxygenation, ventilation and perfusion to core organ systems such as the brain and heart, and (3) to manage any coexisting diseases. Anesthesia is achieved with a "cocktail" of drugs that induce unconsciousness, amnesia, temporary muscle paralysis, and also inhibit the body's responses to pain. The anesthetist delivers these drugs and monitors the outcome through direct clinical observation of the patient and through monitoring devices with visual and auditory displays, making adjustments when needed.

According to Gaba (1994) there are anesthesia situations that require particularly careful allocation of attention, but where current monitoring and display technologies may fall short. Moreover, the greatest danger in anesthesia may lie in attentional capture. As Coiera et al. (1996) have noted, attentional capture can occur because anesthetists look at information but do not process it sufficiently to register its meaning, because they monitor selectively according to relevance, or because they do not want to abandon a complex mental task before it is completed. The anesthetist's attention must also be allocated to judging whether, how, and when to act so that the desired state is achieved effectively—good timing is a hallmark of anesthesia expertize (Nyssen and Javaux, 1996). Displays that reduce the uncertainty of whether, how, and when to act are rare but would reduce this burden on the anesthetist's attention.

1.2. *Attention and modality*

Gaba (1994) does not describe levels of attentional control over monitoring or how attention is alerted. Yet Weinger's vision included real-time continuous monitoring and recognized the anesthetist's need to stay ahead of events. It is important to introduce some basic ideas in attention before examining how well Weinger's vision is being realised.

Fig. 1 shows how the anesthetist's focal and peripheral attention might be controlled during monitoring. Exogenous and endogenous orienting of focal attention are distinguished (Posner, 1980; Berger et al., 2005). Exogenous orienting occurs when the anesthetist's focal attention is captured by external events or properties of the environment such as change (particularly when it is unexpected), interruptions, alerts and other distractions (e.g., Remington et al., 1992). Endogenous orienting occurs when the anesthetist's internal motivations or dispositions guide focal attention, such as goals, plans, expectations, emotions or values (e.g., Folk et al., 1994).

Exogenous factors may guide behavior without necessarily capturing focal attention, as when signals (e.g., the background sound of air flow in the anesthesia machine) have low intensity or are denied full attention due to competing tasks. This has been called *preattentive reference* (Woods, 1995) reflecting the concept of preattentive processing in attention research (Broadbent, 1977). Preattentive reference can be shaped by endogenous factors such as plans, expectations, values and emotional significance (e.g. a potentially dangerous breathing pattern). Participants process information faster and more thoroughly if it is expected or has high arousal value (Anderson, 2005; Dolan, 2003). As Fig. 1 indicates, expectations and values may also evolve over prolonged practice as the anesthetist internalizes the pacing and event structure of anesthesia, so that focal attention is oriented endogenously rather than exogenously (Jonides, 1981). Preattentive reference will capture focal attention if signal intensity increases or if competing tasks finish.

Fig. 1 describes the operation of attention without referring to the contribution of different sensory modalities. However, Weinger's vision included the use of multiple modalities. How effective are different modalities for the control of attention during monitoring and how might they operate together?

As shown in Table 1, the visual, auditory and haptic modalities differ in terms of whether information persists in time, whether information is delivered in a localized, ubiquitous or personal manner, whether sensing the information is optional or obligatory, whether the information is

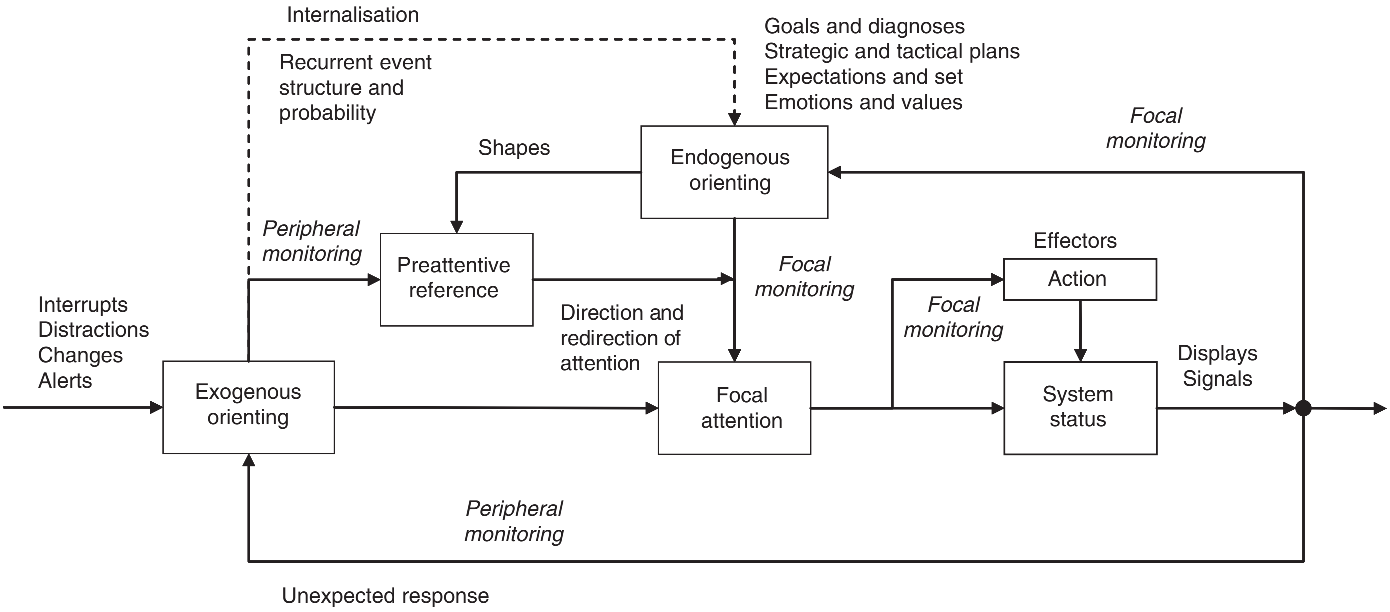

Fig. 1. Control of attention through exogenous (external) and endogenous (internal) orienting. Diagram shows that endogenous control can develop through internalization of exogenous factors through experience.

Table 1
Contrast between fundamental properties of visual, auditory and haptic modalities of information presentation

Visual	Auditory	Haptic
Persistent—Signal typically persistent in time so that information about past has same sensory status as information about present.	Transitory—Signal happens in time and recedes into past: Creating persistent information or information about past are design challenges	Transitory—Signal happens in time and recedes into past: Creating persistent information or information about past are design challenges
Localized—Can be sensed only from specific locations such as monitors or other projections (eyeballs needed)	Ubiquitous—Can be sensed from any location unless technology is used to create localized qualities	Personal—Can be sensed only by the person to whom the display is directed (unless networked or shared).
Optional—There are proximal physical means for completely eliminating signal (eyeballs, eyelids, turn)	Obligatory—There are no proximal physical means for completely eliminating signal (unless earplugs block signal)	Obligatory—There are no proximal physical means for completely eliminating signal (unless remove device)
Moderately socially inclusive—Others aware of signal but need not look at screen	Socially inclusive—Others always receive signal unless signal is sent only to an earpiece.	Not socially inclusive—Others probably unaware of signal.
Sampling-based monitoring—Temporal sampling process needed for coverage of all needed variables.	Peripheral monitoring—Temporal properties of process locked into temporal properties of display	Interrupt-based monitoring—Monitoring based on interrupts
High information density—Many variables and relationships can be simultaneously presented	Moderate information density—Several variables and relationships can be simultaneously presented	Low information density—Few variables and relationships can be simultaneously presented

potentially socially inclusive, whether monitoring is achieved through sampling, peripheral awareness or interrupt, and the information density of the modality. Clearly, some modalities are better suited to carrying certain kinds of information over others. Importantly, modalities may differ in how well they provide information focally or peripherally, and how well they control attention through exogenous factors.

The most successful uses of monitoring modalities appear to be those in which the modality is well-mapped to the attentional demands of the task (Watson and Sanderson, in press). For example, Ng et al. (2005) show that by being a very effective exogenous cue, a vibrotactile wristband leads to a higher identification rate for heart rate alarms than does an auditory display. Using the terminology of Table 1, putting a discrete reminder into a transitory modality with low precision but with obligatory properties is an appropriate use of the haptic modality and it leaves the visual and auditory modalities free for other tasks.

In principle, using multiple modalities in parallel can increase the attentional and performance capacity of the anesthetist. In a well-known theory, Wickens (1984) proposed that people have multiple separate pools of attentional resources. He distinguished between modalities of presentation (visual, auditory, haptic, etc.), codes of processing (spatial, verbal), and modalities of response (manual, vocal). Task performance can improve if different streams of information are presented in different modalities (Wickens, 2002). However, delivering information in different modalities is not always the best way of increasing the anesthetist's information processing capacity. Attention can be inappropriately captured by one modality at the expense of another, as studies of driver distraction with cell phones attest (Strayer and Drews, 2004). Moreover, information that must be integrated to be understood is probably better delivered in one modality rather than split across different modalities (Wickens and Carswell, 1995). Overall, Wickens' theory does not provide a robust framework for allocating information to modalities so that focal and peripheral attention are carefully controlled.

The sections that follow outline progress in how Weinger's vision has been realised to date, focusing on two visual and two auditory medical monitoring displays: (1) "ecological" visual displays, (2) head-mounted displays (HMDs), (3) advanced auditory displays, and (4) auditory alarms. Throughout, findings are related to the model of attention in Fig. 1 and the characteristics of modalities in Table 1.

2. Ecological displays

Weinger envisages that EID-based displays will support the use of closed-loop control for drug administration. Given advances in pharmacokinetics and pharmacodynamics, future drug delivery may be based on computer-controlled variable infusion ("target controlled infusion") rather than on bolus or fixed continuous infusion (Locher et al., 2004). Such systems will have to be understood and monitored by anesthetists. Approaches to display design such as EID may help.

The content of an ecological display is determined by analyzing the *work domain* within which the display will support activity. A work domain analysis (WDA) describes the purposes, priorities, functions and physical aspects of a system in a way that reveals first principles on which the system operates and means-ends connections between purposes, priorities, functions and physical aspects. The WDA is a defining requirement of EID (Vicente, 2002; Burns and Hajdukiewicz, 2004)—without it, displays are best described as configural graphics.

An ecological display reveals the relationship between different functions in the work domain, the constraints within the work domain, and its operating boundaries. When a patient's vital signs, and derived physiological properties, are displayed against this backdrop, the patient's state can be understood in terms of the first principles of physiological functioning. Ecological displays can reduce inappropriate attentional capture by integrating information in a way that quickly conveys the implications of the patient's status, supporting perception, decision and action at the level of behavior—skill-, rule- or knowledge-based—that involves least workload (Vicente, 2002).

2.1. Cardiovascular and hemodynamic monitoring and control

Several groups have developed advanced displays based on configural graphics to support faster detection of hemodynamic or cardiovascular (CV) abnormalities (see summary in Momtahan and Burns, 2004). Many of these displays have been inspired by EID but are not based on a formal WDA. However, as Burns and Hajdukiewicz (2004) point out, sometimes the content of displays such as that developed by Zhang et al. (2002) can be found in the balances, processes, and physiology levels of a WDA of anesthesia such as the WDA performance by Hajdukiewicz et al. (2001).

Zhang et al. (2002; Study 2) displayed eight vital signs plotted over time in four views (see Fig. 2a). The egg-like shapes are red, and represent heart rate and cardiac output (height). The transparent holder of the egg-like shapes gives systolic and diastolic blood pressure (BP) as its top and bottom values and the position of the shape forward or backwards gives oxygen saturation. The undulating curtain-like shape at the back represents inspired and expired respiration with $ETCO_2$ waveform visible from an overhead view. Normal reference markers are provided that help the viewer detect change. With this display, anesthesiologists were faster on two out of four test scenarios and showed better situation awareness in one out of four scenarios, which is not a strong result.

A further display, in which separate graphic objects showed the relationship between CV variables, helped diagnosis (Blike et al., 2000). When Zhang et al. (2002, Study 1) used this display, however, benefits were found only for certain anesthesia scenarios, perhaps because there was no trend information or digital readouts of vital signs. Jungk et al. (1999) developed a configural display that related cardiac venous return (preload) and resistance (afterload) through a dynamic version of the well-known volume–pressure diagram. Participants were slower to restore hemodynamic parameters to their normal states with the configural display but they were more likely to reach a solution. Subsequent studies have used more abstract "pipe"-like graphics to represent cardiac functioning (Agutter et al., 2003) and pulmonary functioning (Wachter et al., 2003) and have found performance benefits for scenarios in which the graphical metaphors were particularly salient. Overall, WDA may lead to displays whose effects can be more reliably predicted.

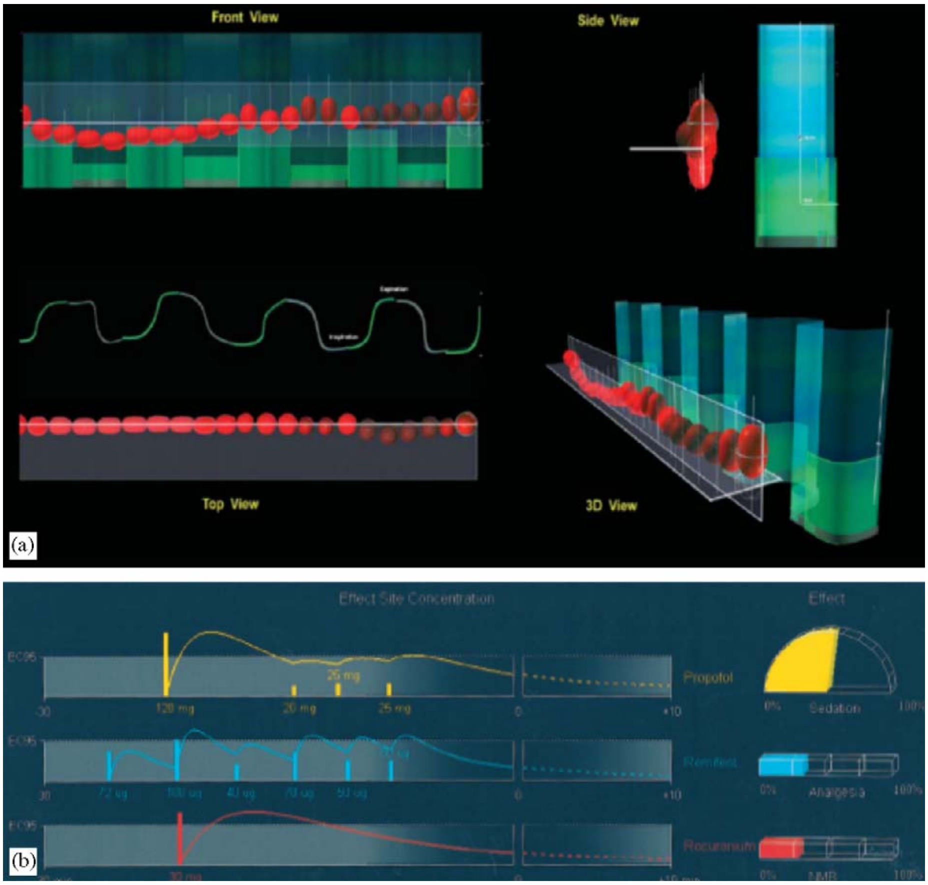

Fig. 2. (a) Configural display for monitoring patient vital signs (Zhang et al., 2002, Study 2). (b) Configural display for monitoring drug end site concentration (Syroid et al., 2002).

2.2. Controlling delivery of anesthesia drugs

Weinger envisaged that EID-based displays would support the use of automatic closed-loop control of anesthesia. Displays developed to date support human-in-the-loop control, but could also help the anesthetist monitor automated controllers and know when to intervene—concerns of Gaba's (1994) that can absorb the anesthetist's attention.

Configural and predictor displays have been developed to help the anesthetist monitor and control effect-site concentration of drugs, whether delivered intravenously (Syroid et al., 2002) or via inhalation (Kennedy et al., 2004). Syroid et al.'s (2002) displays showed predicted effect-site concentrations over time for drugs supporting analgesia, sedation, and neuromuscular blockage (see Fig. 2b). Anesthesiologists using the predictor display were able to reach target effect-site concentrations faster and to maintain them closer to desired levels than those using a conventional display (Syroid et al., 2002) and reported lower rated workload. Similarly, Kennedy et al.'s (2004) predictor display showed effect-site concentrations over time for sevoflurane (an inhaled anesthetic gas). Anesthetists made changes sooner with the predictor display, but there was no difference in overshoots/undershoots or stability.

2.3. Challenges for EID in the medical domain

In Weinger's vision, there is an emphasis on direct sensing and display of variables at different levels of physiological organization, a concern shared with Blike. This comment is well-informed, first with respect to the use of WDA for EID and second with respect to technical developments in anesthesia.

First, control is more effective if a display provides direct information about the effect of control on higher-level rather than lower-level properties in the work domain. However, it can be challenging to represent physiological functioning in the formal WDA framework typically used in EID (Momtahan and Burns, 2004). We have limited sensors and incomplete knowledge of how to model physiology in general, let alone in each individual patient (Hajdukiewicz et al., 2001). When many higher-order variables of a WDA cannot be sensed but must be derived, controllers can find it difficult to distinguish sensor and system failures if there is poor sensor redundancy (Reising and Sanderson, 2002, 2004) and the advantages of EID displays may diminish if sensors are unreliable (St Cyr and Vicente, 2005).

Second, the human body has complex internal control loops that are not easily captured in the standard WDA framework. The latter point is particularly evident in intensive care units and has driven Miller (2004) to propose an entirely different framework for performing WDA, based in part on bio-regulatory mechanisms and gradient dissipative structures theory. Ecologically inspired displays based on this approach have been tested with promising results (Miller and Sanderson, 2003).

Third, technological developments that produce non-invasive measures of higher-level physiological properties and balances are exceptionally valuable. Pulse oximetry, introduced in the 1980s, provides a non-invasive way of measuring arterial blood saturation, a key requirement for effective oxygenation. Non-invasive monitoring of respiration continues to develop (Folke et al., 2003). In the late 1990s and early 2000s monitoring the patient's depth of anesthesia or level of consciousness—the so-called "holy grail" of anesthesia—has been advanced with neurophysiological monitoring, including creation of the bispectral index (BIS) (Myles et al., 2004) and automatic closed-loop control of BIS levels has been investigated (Struys et al., 2004). Cognitive engineers have argued that the analysis of information needs and sensor adequacy that WDA can provide should drive research and development in instrumentation engineering (Reising and Sanderson, 2002) including for medicine.

Finally, Sanderson et al. (2000) and Watson and Sanderson (in press) argue that EID should be developed further if it is to extend to non-visual as well as visual displays in medicine. Non-visual modalities introduce possibilities outlined in Table 1 that are important for who should receive information and when. For example, team coordination may be better achieved in the auditory rather than visual modality. In summary, EID should be more fully informed by the other analytic phases of the cognitive work analysis framework from which it emerged, such as the analysis of workers' strategies, social organization, and competencies.

3. Head-mounted displays

Weinger's vision included "a lightweight HMD with 3-D audio and video display". HMDs compensate for some of the limitations of fixed visual displays for monitoring (see Table 1). Although visual displays offer high precision, they provide a localized, optional view of patient data that depends upon the anesthetist having an effective sampling strategy if important events are not to be missed. As noted in an early study of HMDs for anesthesia (Block et al., 1995), HMDs provide a proximal display of information so it can be consulted more readily alongside timeshared perceptual-motor tasks. The HMD imposes ubiquitous and obligatory properties while still providing some of the precision of a visual display.

Advantages and disadvantages of HMDs for anesthesia settings have been outlined in Sanderson et al. (2005)—here we examine their progress in light of Weinger's vision and how they use the visual modality.

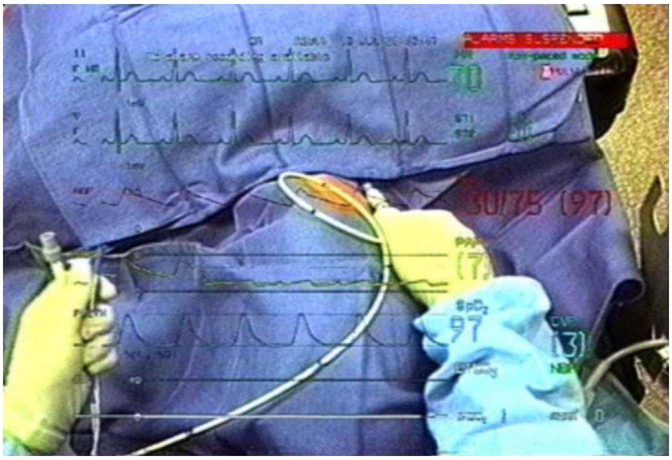

Fig. 3. View of patient through head mounted display (Via et al., 2003).

3.1. Using HMDs for anesthesia monitoring

Relatively little research has been performed on HMDs for anesthesia monitoring compared with their use in other areas of medicine such as laparoscopic surgery. The reduced need to scan monitors is considered an advantage. In Block et al.'s (1995) study anesthesiologists used an opaque, monocular HMD (Private Eye^{TM}, Reflection Technology, Cambridge, MA) which met with interest by most participants despite physical drawbacks with the device that later models have largely overcome.

Since 2000, transparent monocular HMDs have been successfully tested (see Fig. 3). In Ormerod et al.'s study (2002), anesthesiologists wore a Microvision^{TM} Nomad HMD (Redmond, WA) and handled a simulated cardiac arrest, heart block, respiratory arrest, airway disconnect, IV disconnect, hypoxia, and bradycardia with low BP in a full-scale patient simulator. Participants spent more time looking towards the simulated patient (but whether at the patient or at the HMD display is unknown) and less time looking around at the visual monitors. In a short followup report, Platt (2004) provided a positive report of informal explorations with the Microvision^{TM} Nomad in which procedures were performed faster.

In a study with a Kaiser^{TM} Electro-Optics PV-40ST HMD (Carlsbad, CA), anesthesiologists wore the HMD during routine induction and intubation in a clinical setting (Via et al., 2002). Participants reported that the HMD allowed them to monitor vital signs almost continuously, requiring less movement and offering a good ability to see vital signs during laryngoscopy (part of the intubation process). Overall, the anesthesiologists considered the HMD valuable and they reported they would use it if display aspects were improved. In a follow-up study in a full-scale patient simulator (Via et al., 2003) anesthetists detected 10 critical events faster with the HMD than with a conventional patient monitoring screen.

3.2. Mixed reality displays

In the above reports, information presented on the HMD was either similar to that on the standard patient monitor (Via et al., 2002) or was a simplified version (Ormerod et al., 2002). In Block et al.'s (1995) study, participants simply wanted a replica of the standard monitoring screen. Yet in Weinger's vision "mixed reality" is noted, in which the HMD enhances the viewed scene with a spatial overlay (a "conformal" image) that carries further important information. There has been very little investigation into the best information to provide on an HMD for anesthesia monitoring and explorations into mixed reality have not started.

Despite this, there are many potential applications for mixed reality. Anesthetists must perform various small procedures in which they interact with the patient's anatomy, as when cannulating a vein to insert a central line, or with anatomically localized physiological processes, as when positioning a sensor to identify deep structures. For example, inserting a needle to perform a peripheral nerve block is often guided by ultrasound which allows the underlying vascular and neural structures to be visualized (Sites et al., 2004). Handling both the needle and the ultrasound device can be awkward, difficult to learn, and prone to causing injury. An HMD that provides a conformal image of the underlying structures could relieve both hands for the motor task and possibly reduce injury.

Similar advantages could be found for positioning a Swan-Ganz catheter, which is usually inserted in the right jugular vein, advanced to the right atrium where the catheter balloon tip is inflated and finally floated to a position in the pulmonary artery. Knowing the location of the tip of the catheter could be greatly aided by a mixed-reality HMD display.

3.3. Potential for attentional capture

As Sanderson et al. (2005) have noted, when used for anesthesia monitoring HMDs may be prone to some of the attentional problems seen with head-up displays (HUDs) in cockpits. To use the terms of Table 1, the HMD converts a localized display to one that is both ubiquitous and personal, and monitoring becomes more peripherally based than sampling based. Wickens (2005) has reviewed many laboratory and full-scale aircraft simulator studies in which unexpected events in the forward view of the outside world are missed or their detection is delayed when participants use an HUD to monitor flight status. Similar attentional capture effects could be dangerous in anesthesia monitoring.

One explanation for the attentional capture effect of HUDs is that display elements on the HUD form a perceptual object, possibly through the Gestalt phenomenon of common fate (Jarmasz et al., 2005). When the display is mounted to the head, as in Weinger's description, rather than to an external fixture, so becoming a personal display (Table 1) common fate may be especially compelling, with the possibility of stronger attentional capture by the HMD as it is monitored. All investigations of HMDs in the anesthesia domain have focused on expected tasks in the forward field of view—conditions under which attentional capture by the HMD is unlikely to occur (Wickens, 2005). However, investigations in our laboratory suggest that participants wearing an HMD are slightly more likely to miss unexpected events in the forward field of view (Krupenia and Sanderson, in press). Overall, HMD-induced attentional capture is an important concern that should be investigated in a full-scale patient simulator.

4. Auditory displays

Weinger's vision includes the use of 3-D audio and a broader range of auditory displays than is currently the case. An auditory display can either (1) provide continuous background information about vital signs, (2) sound when there is a significant change in vital signs, or (3) sound at regular intervals (Seagull et al., 2000). The best arrangement depends on how the underlying parameter is measured, how closely it needs to be monitored, and what the other demands on attention might be. There is a growing amount of research and development of auditory displays for anesthesia but very little involving 3-D or "spatialised" audio. Most properties that anesthetists monitor do not have a natural 3-D spatial mapping, in contrast to aviation or air defense in which 3-D audio can become a 3-D conformal display. Some key current activity is concerned with the development of sonifications and earcons for monitoring vital signs.

4.1. Sonification

A continuous auditory display already in existence in anesthesia is pulse oximetry which conveys information about oxygen saturation in arterial blood. The rate of a series of beeps conveys heart rate and the pitch of the beeps conveys percentage oxygen saturation. Pulse oximetry has been exceptionally successful since its introduction in 1983 (Webb et al., 1993). Craven and McIndoe (1999) found that pulse oximetry using the variable tone to indicate oxygen saturation led to significantly faster detection of desaturation than pulse oximetry with a fixed tone, even though audible pulse oximetry has only the moderate precision associated with most auditory displays (Table 1). Morris and Mohacsi (2005) have shown that anesthesiologists consistently overestimate the oxygen saturation indicated by variable tone pulse oximetry and underestimate the degree of change indicated.

Nonetheless, the benefits of variable tone pulse oximetry are well established. A possible extension of the concept to end-tidal carbon dioxide (ETCO$_2$) monitoring has been noted by Craven and McIndoe (1999) amongst others. The importance of conveying information about ETCO$_2$ was recognized at a 2004 alarms workshop of the Anesthesia

Patient Safety Foundation (APSF) which subsequently proposed as a practice standard that when pulse oximetry is used, the variable pitch tone and the low threshold alarm should be audible, and when capnography is used the hypoventilation alarm should give an audible signal. Discussions at the ASPF workshop noted possible further roles for sonification (Olympio, 2004).

A variable-tone sonification of $ETCO_2$ concentration could provide further help for monitoring. Lampotang et al. (1998) tested anesthetists' time to diagnose problems in four scenarios using a full-scale patient simulator, comparing detection time with vs. without variable-tone pulse oximetry plus visual capnography displays. For an oxygen supply failure scenario, time to diagnose was significantly shorter with pulse oximetry and capnography. However, there was no change in $ETCO_2$ for the oxygen supply failure scenario. In the other three scenarios $ETCO_2$ did change, but diagnosis time was not faster with the pulse oximetry and capnography. If capnography had included a variable-tone sonification of $ETCO_2$, there might have been faster response for these scenarios also.

Several research groups have developed sonifications of respiratory parameters, including $ETCO_2$. Loeb and Fitch (2002) found faster identification of various patient events when a visual display was supplemented with a pulse oximetry sonification including BP information, plus a novel sonification of respiratory parameters. Watson and Sanderson (2004) used standard pulse oximetry plus a novel sonification of respiratory parameters such as RR, $ETCO_2$ and V_T, and tested anesthetists' accuracy of identifying the state and trend of patient vital signs. Accuracy with sonification alone was the same as with visual displays, but with sonification alone participants could perform time-shared tasks better (see Fig. 4). Seagull et al. (2001) found faster detection with visual displays alone, but better performance of a time-shared task with sonification alone. Draeger^{TM} have installed in their most recent anesthesia machines an audification (amplification) of patient breathing, but a respiratory sonification that includes information about $ETCO_2$ has yet to appear in commercial equipment.

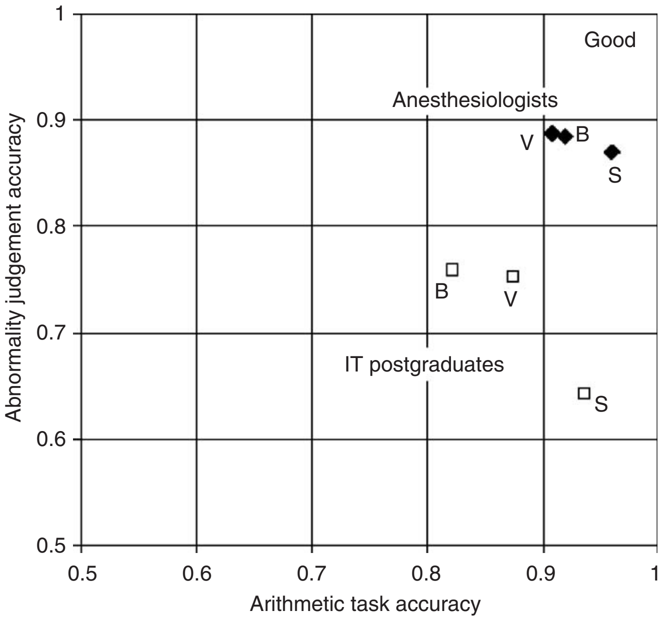

Fig. 4. Sonification results for monitoring (Watson and Sanderson, 2004). S = sonification only, V = visual display only, B = both sonification and visual display.

4.2. Earcons

The earcon is a member of a set of discrete sound motifs bound by a simple grammar in which values and relationships can be represented (Blattner et al., 1989). A medical example is BP earcons (Watson and Gill, 2004). During intermittent BP monitoring, a non-invasive BP cuff inflates every few minutes to take a reading, after which an earcon can sound to signal the new reading. In one version, each earcon conveys information about the normal systolic and diastolic BP readings (*N*) and the current readings (*C*). Each reading is mapped on to a short tone at a musical pitch indicating the BP reading. When assembled to make the earcon, the tones are played in the order *N*–*C*. The *N*–*C* earcon leads to better estimates of current BP reading than a *C* earcon alone (Watson and Gill, 2004). Tests against standard visual BP monitoring are forthcoming.

Because auditory displays are ubiquitous, obligatory, and socially inclusive (see Table 1) an important concern is how many auditory displays can work together without overwhelming the listener or creating annoyance to others, and how such issues can be overcome. This is one of many important areas for future research.

5. Alarms

Missing from Weinger's (2000) vision is the medical monitoring display more closely studied than any other—auditory alarms. An auditory alarm is designed for interrupt-based monitoring of abnormal states rather than peripheral monitoring of abnormal states (Table 1). Auditory alarms represent an exogenous solution to the need to avoid attentional capture and avoid missing changes (Fig. 1).

Alarms often annoy anesthetists and fail to provide them with the information they need, so Weinger's omission of alarms is not surprising. Despite a long tradition of research into auditory alarms in critical care environments (see summaries in Edworthy and Hellier, 2005; Weinger and Englund, 1990) studies continue to appear. In his comments, Blike addressed alarms more directly, noting that medical devices should become smarter and more aware of the current mode or operative context (Seagull and Sanderson, 2001) so that alarms are never a nuisance.

Intelligent alarm systems have been investigated for years. The most successful solutions do not involve strong artificial intelligence but instead use simple algorithms to suppress alarms that are uninformative, irrelevant, or that simply reflect artefact. The latest international standard for medical equipment alarms, IEC 60601-1-8, addresses such issues. A further concern is that alarms do not reliably identify their source, so that operating room personnel often lose time investigating the source and cause of an alarm. IEC 60601-1-8 addresses this concern by proposing melodic alarms, as discussed below.

5.1. Melodic alarms

IEC 60601-1-8 suggests that alarms should distinguish sources by using simple melodies linked either to the physical functioning of the source or to the way alarm states might manifest in the source. For example, a descending series of notes represents decreasing oxygen saturation and therefore an oxygen-related alarm. IEC 60601-1-8 includes descriptions of the mappings (“mnemonics”) such as the above to help people learn and remember the mappings (see also Block et al., 2000).

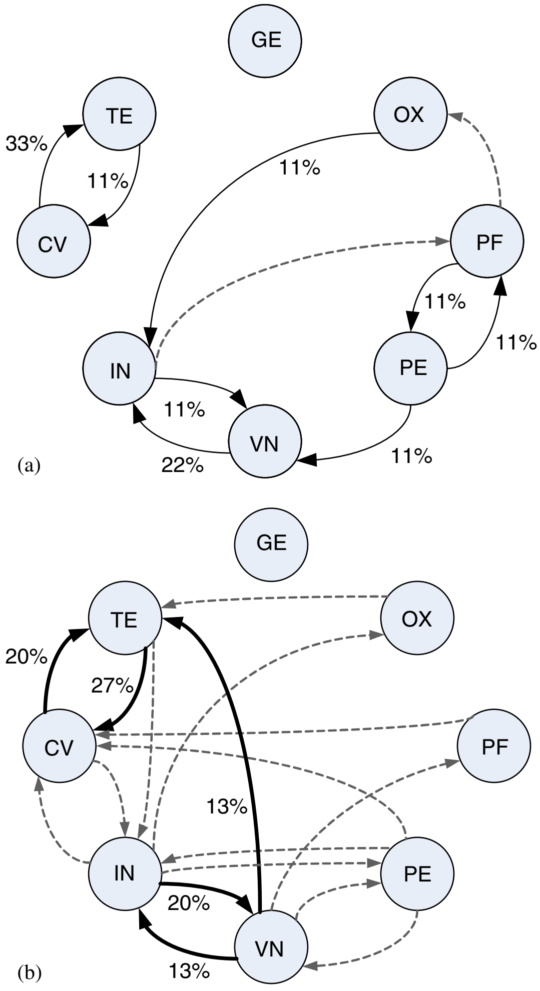

Fig. 5. Alarm confusions for IEC 60601-1-8 (Sanderson et al., 2006). GE = general alarms, OX = oxygenation, PF = power failure, PE = perfusion, VN = ventilation, IN = infusion, CV = cardiovascular, TE = temperature. Figure shows percentage of participants who confused one alarm for another on more than 25% of occasions.

Unfortunately, the IEC 60601-1-8 melodic alarms were not systematically tested for intelligibility, discriminability, and ease of learning before the standard was published. In two subsequent studies, non-healthcare participants confused certain pairs of alarms even after two sessions of training (Williams and Beatty, 2005; Sanderson et al., 2006). In the Sanderson et al. study, participants learned the alarms either with or without the IEC 60601-1-8 mnemonics. Some confusions occurred in both learning conditions because the alarms are perceptually similar (see Fig. 5). For example, the temperature (TE) and CV alarms both have a rising pitch. Other confusions were idiosyncratic, especially in the non-mnenomic group.

One danger is that if mnemonics apply equally well to two alarm melodies, then mnemonics will strengthen confusions. Moreover, users may develop a false confidence in their ability to identify alarms. It is unknown whether people’s ability to identify alarms with the IEC 60601-1-8 melodies can reliably become automatic, capacity-free, and capable of being performed alongside other activities without loss in accuracy or speed. Further studies of the IEC 60601-1-8 alarms should be run with healthcare participants in a simulator.

5.2. Urgency mapping

Many researchers argue that how urgent alarms sound should reflect how urgent alarms actually are (Mondor and Finlay, 2003; Edworthy and Hellier, 2005), so that attention is attracted through exogenous means. Mondor and Finley argue that urgency mapping is needed because alarms must be heard when the anesthetist’s attention is elsewhere. If an alarm has to be processed to the level of meaning before its urgency can be determined, then the filtering that acts on unattended stimuli in selective attention and that prevents unattended stimuli from being fully processed will also prevent the anesthetist registering the urgency of an alarm. However, some counterarguments are as follows.

First, apart from basic low, medium and high priority levels, it may not be worthwhile differentiating alarms by urgency. The urgency of a situation will depend on the clinical context as interpreted by an expert listener (Seagull and Sanderson, 2001; Woods, 1995). Guillaume et al. (2003) show that associations can make alarms more or less urgent-sounding than their acoustic properties alone suggest. It is more important to know what the alarm is in order to judge its urgency *in context* than to have an a priori mapping to urgency.

Second, alarms have strong subjective importance to healthcare workers. Arousing or emotional stimuli do not need to be processed to the level of meaning to capture attention (Anderson, 2005; Dolan, 2003). Unattended auditory cues with strong subjective significance may therefore be enough to reorient attention. However, this should be directly tested.

Table 2
Key points and challenges for medical monitoring technologies in multiple modalities

Theoretical viewpoint

- Designing medical monitoring involves designing attention
- Attention works differently in different modalities
- Understanding medical monitoring involves understanding multimodal attention

Findings of state-of-the-art review of medical monitoring in different modalities

- *For visual displays*: display design theories should extend to all modalities
- *For head-mounted displays*: need to investigate possible dangers of attentional capture
- *For auditory displays*: need to investigate intelligibility and annoyance
- *For alarms*: need to take context into account is a pervasive challenge

Challenges

- Need for more thorough human factors-based development and testing of displays
- Methods for identifying information needs should also identify attentional needs
- Need theories of multimodal attention better able to directly guide display design.

Third, requiring an alarm classified as urgent to always forcefully attract attention may be counterproductive if the alarm is sometimes irrelevant, uninformative, or reflects artefact. Participants match their response rates to the realibility of an alarm (Bliss et al., 1995). If an alarm with a reliability of 50% is responded to 50% of the time, the expected hit rate is 25% and the alarm will be handled only 25% of the time, no matter how urgent it sounds. Urgency mapping will therefore not reliably attract a response unless an alarm has near-perfect diagnosticity and sensitivity.

In summary, the IEC 60601-1-8 melodic alarms may be dangerous, but probably for different reasons from the ones Mondor and Finlay (2003) suggest—they are confusable and may create inappropriate confidence in misidentifications. Overall, until context can reliably be used to manage alarms, alarms will continue to be problematic. Continuous auditory displays of vital signs with "self-labelling" alarm states in extreme ranges, may provide a better solution by supporting attention through preattentive reference.

6. Conclusion

Current research in the multimodal world of medical monitoring shows some progress towards Weinger's vision but as Table 2 shows, there are also some areas that remain quite underdeveloped. Where might research and development best proceed in the future?

First, an important aspect of Weinger's vision as well as Blike's later comments is the emphasis on human factors research and testing. The need for human factors input into the design and evaluation of medical monitoring equipment is still not widely appreciated amongst medical equipment manufacturers, nor is there an appreciation of the most effective techniques for doing so. Blike recommended that basic HF principles, including user testing, should be written into medical device standards—we see this for example in ANSI-AAMI HE-74-2001. However, Weinger (2002) projected that "years of extensive research and testing" would have to precede the kind of information ecology he envisioned. For revolutionary technologies, revolutionary design and evaluation techniques may be needed.

Second, we must develop a robust framework for determining where important information needs of the anesthestist are unfilled. Weinger and Blike identify some needs—how can we be sure they are the right ones? As Reising and Sanderson (2002) note, WDA can be used to identify information needs and so guide technical innovation to where it will be effective, rather than a gratuitous imposition. We can also use WDA to evaluate the impact of new sensor technologies and new forms of instrumentation (Benda and Sanderson, 1999). Alongside information needs, though, we should identify attentional needs (Watson and Sanderson, in press).

Third, we need strategic research into attention in different modalities that goes beyond much laboratory research performed today which depends upon simple tasks delivered in discrete, independent trials that last only a few seconds, unlike medical monitoring. We must develop and test models of attention in different modalities that let us evaluate whether novel information displays will be effective. For example, an HMD combines properties from more traditional visual and auditory displays (see Table 1). How can an analyst quickly determine how effective the HMD will be alongside other information sources, given the goals and concerns of anesthesia, the operation of attention shown in Fig. 1, and the properties of modalities shown in Table 1? Further developing and testing such models would be a very important human factors contribution to the multimodal world of medical monitoring.

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Penelope Sanderson is Professor of Cognitive Engineering and Human Factors at The University of Queensland in Australia, and Director of the ARC Key Centre for Human Factors. She received her Ph.D. in 1985 from University of Toronto.