Shaped by Design "How User-Interface Design Influences Medical Decision Making: The Role of Monitoring Equipment in Anesthetic Practice"

by

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TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

Chapter 1

INTRODUCTION

User-interface design has seen noteworthy developments over recent decades on account of a "paradigm shift from systems' point of view to user's point of view," but while this direction has offered considerable insights into the variability of user needs and capabilities, effective graphical data representations remain a persistent challenge. This is especially so in the case of "information-intensive applications in which the *organization, display* and *manipulation* of dense, complex data are problematic" [Nardi, 1993, p. 6]. The source of difficulty appears to revolve around the concept of 'mental models' and the effort dedicated to capturing them in user-interface design. Mental models, a particularly prominent concept in human-computer interaction (HCI), are the cognitive constructs with which users make sense of external reality. The aim has been to match interfaces to that of the user's mental model, which would theoretically facilitate ease of use by virtue of "translat[ing] [thoughts] into…physical actions required by the system" [Nardi, 1993, p. 10]. Inasmuch as this approach may have some utility in bridging the gap between users and systems, it fundamentally treats user-interfaces as mere representations of perception, rendering it rather *passive* and inert. Besides having to resolve the often poorly formed, unstable, and incomplete nature of mental models, user-interface designed as such could not possibly hope to assume an *active* role in facilitating information integration and complex problem-solving.

Given the extent to which information systems are heavily relied upon for a number of complex applications, user-interfaces should actively "direct cognition" [Nardi, 1993, p. 10] rather than merely represent it. In shifting the user's cognitive resources towards the right data, at the right time, they "spar[e] [users] the need to create [and maintain] a 'mental model'" [Nardi, 1993, p. 10], thereby easing overall mental workload. In this sense, interfaces effectively function as decision enablers, drawing attention to relevant information while "constrain[ing] user behavior" [Elm, 2002, p. 285]. This is unquestionably relevant in complex domains characteristic of high-risk industries i.e. medical, in which tasks are tied to a number of mediating variables that render decision making not only difficult but also particularly prone to error. More often than not, decisions within intensive care environments are made "rapidly and under times of distress" [Wright, 2011, p. 484]. To fully assess and integrate both observable and subtle data variables for proper 'sensemaking,' clinicians require a great deal of on-screen data referencing and monitoring.

Nowhere is this more striking than in medical anesthetic practice in which the ubiquity of electronic patient monitoring systems calls for user-interfaces to be "at the same time, *usable* and *useful*" [Pantazi, 2006, p. 829]. When data displays are visually structured for decision support, they not only allow for efficient information retrieval and integration, but more importantly, they supply situational estimates that facilitate future data projections. As anesthesiologists are invariably tasked with developing "differential diagnos[es] quickly and accurately" [Wachter, 2006, p. 635], how data aid them in anticipating changes to patient physiological status is critical to prompt remedial action and overall proper clinical care. As such, data visualizations designed to "capitalize on the characteristics of human perception and cognition" [Elm, 2002, p. 285] involved in change detection serve as useful cognitive tools for anesthetists to maintain keen and continuous situational awareness. Without which, clinicians are certainly prone to commit both active and latent errors in diagnosis and treatment.

Background

At present, medical errors within the surgical theatre continue to occur despite technological advances and improved patient safety standards. Such errors account for an estimated 44,000 to 98,000 deaths each year, which exact approximately $29 billion in costs to hospitals nationwide [Corrigan 1999]. Moreover, the decentralized nature of the health care system further complicates the issue, making systematic large-scale error detection, documentation, and tracking difficult, if not nearly impossible. The lack of clear guidelines, little to no anonymity, and potential for disciplinary action all pose significant barriers to public reporting. Indeed, as few as 14% of all medical errors are actually reported [OIG 2012], and "for decades, virtually all harm done have been labeled inevitable" [Pronovost, 2009, p. 1273], effectively understating clinical accountability. While there are admittedly inherent risks associated with intensive care, medical errors as demonstrated in a number of retrospective studies are largely *preventable* [Angheluta, 2010, p. 23]. Considered as "'never events,'—events that should never happen in a hospital—are occurring at alarming rates," according to the American Association for Justice [AAJ n.d.], suggesting that patient safety measures are still fundamentally reactive at best.

As such, many cases of preventable medical errors consequently draw attention to themselves as malpractice claims—not least of which are surgical anesthesia adverse events. It was in reaction to the increasingly high malpractice insurance premiums that the American Society of Anesthesiologists (ASA) Closed Claims Project was established [Metzner 2011] in an effort to investigate the scope of adverse anesthetic outcomes. While anesthetic mishaps sufficiently serious enough to bring about litigation are effective in penalizing medical negligence, they fall short of deterring grave medical errors. As revealed in the Closed Claims database that spans over four decades since its inception, the most common complications from anesthetic-related incidents between 1990-2007 result in death, followed by nerve injury and permanent brain damage [Metzner 2011]. Yet, much remedial action stemming from legal and regulatory scrutiny does little to uncover the nature and source of anesthetic risks.

As "[f]actors…that may have predisposed anesthetists to err have, with a few exceptions, not been analyzed" [Cooper, 2002, p. 277], it remains unclear why both novices and "anesthesiologists with years of experience made serious errors" [Schwid, 1992]. Unlike errors in other high risk domains i.e. nuclear power and aviation, which are often highly visible and immediately followed by exhaustive investigation, anesthetic errors involve a chain of subtle events, whether intended or unintended, that are characterized by a high degree of complexity and unpredictability "not immediately comprehensible" [Gaba, 1987, p. 670]. Within the evolution of events is a window of opportunity for action; failure to respond due to inadequate early detection could produce a domino effect of events leading to a critical incident. While investigations of anesthetic mishaps have "suggested that many are due to human error rather than equipment failure" [Gaba, 1987, p. 671], there as yet been no established standard for uncovering the etiology of human error specific to the practice of anesthetic monitoring.

Research Aims

Given that anesthetists rely on monitoring equipment for a number of clinical tasks, the goal of the study is to draw a positive correlation between anesthetic performance and equipment use—more specifically, to investigate the extent to which user-interfaces on anesthetic monitoring equipment directly affect clinician's situation awareness (SA), and hence, decision making. As such, the following hypotheses are drawn:

H1: Visualized data is positively correlated with improved perception.

H2: Visual attributes such as shape, size, and color have a positive correlation to improved comprehension.

H3: Visual patterns are positively correlated to improved prediction.

These hypotheses examine the three aspects of cognition that define SA.

Chapter 2

LITERATURE REVIEW

User-interface Design

At present, the widespread use of information computing systems invariably calls attention to user-interfaces and the level of care with which designers must accommodate human perceptual and cognitive abilities. The focus has appropriately been on system usability, which essentially "emerges from understanding the needs of the users, using established methods of iterative design, and performing appropriate user testing" [HIMSS, 2009, p.3]. While such user-driven metrics have reliably set the stage for more intuitive design outcomes, little attention has been devoted to "context-dependent representations" [Pantazi, 2006, p. 829]—in particular, the ways in which complex environments must be visualized to best lend support for real-time, accurate, situation awareness (SA)—that is, the comprehensive, holistic alertness to the environment necessary to achieve a state of preparedness for action.

There appears to be a "knowledge acquisition bottleneck" [Pantazi, 2006, p. 830] frequently experienced in dynamic, multidimensional contexts that render adequate situation awareness (SA) and subsequent decision making appreciably difficult [Durso, 2008]. This connection between user-interfaces and complex contextual SA has not been explored in any significant detail largely due in part to the assumption that usability of an interface naturally translates to usefulness—for knowledge-intensive decision making. On the contrary, "[h]ighly *usable* systems are often less *useful* because they typically solve trivial problems (e.g., generic, repetitive tasks)" [Pantazi, 2006, p. 830]. As such, the challenge for user-interface design should not end at usability but should continue towards an optimal balance between simplicity of design and complexity of SA (Figure 1).

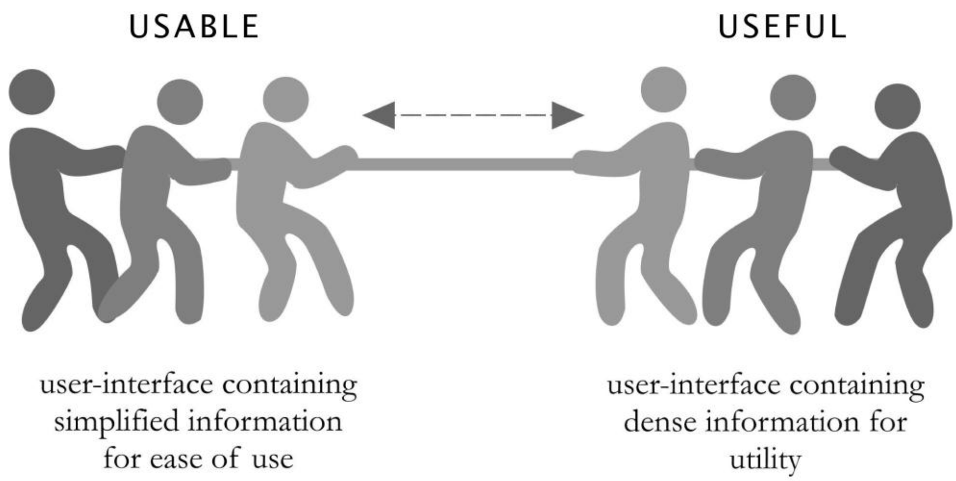


Figure 1. Usable vs Useful. The process of user-interface design that attempts to balance simplicity of design and complexity of data.

Granted, complex SA has undergone rigorous analysis in high-risk industries such as nuclear power and aviation, but these are engineered systems, not "*natural* systems, i.e. the patient," [Drews, 2008, p.783], which present a host of separate interface design issues. While engineered systems exhibit technical predictability on account of well-specified controls, the same cannot be said of monitoring natural systems, which are inherently variable and often not easily quantifiable. Such systems are characterized by a degree of uncertainty that chiefly stems from poorly understood processes wherein the "[c]ause-effect relationships are not clear-cut,…[such that they produce] an uncertain predictive value" [Gaba, 1987, p. 671]. This is nowhere more apparent than in anesthetic patient monitoring in which the various patient physiological variables displayed on monitor screens are subject to change at any given moment—at times almost arbitrarily—that must be continually assessed and integrated for adequate SA and optimal anesthesia care.

Monitoring Displays

Since their introduction into intensive care in the 1970s, patient physiological monitoring displays have seen little improvements. The standard single-sensor-single-indicator (SSSI) design (Figure 2) provides waveform data along with numerical values that, while instrumental insofar as supplying anesthetists with real time feedback of the patient's vital signs, requires clinicians to conduct "sequential piecemeal data gathering," [Drews, 2008, p. 783].

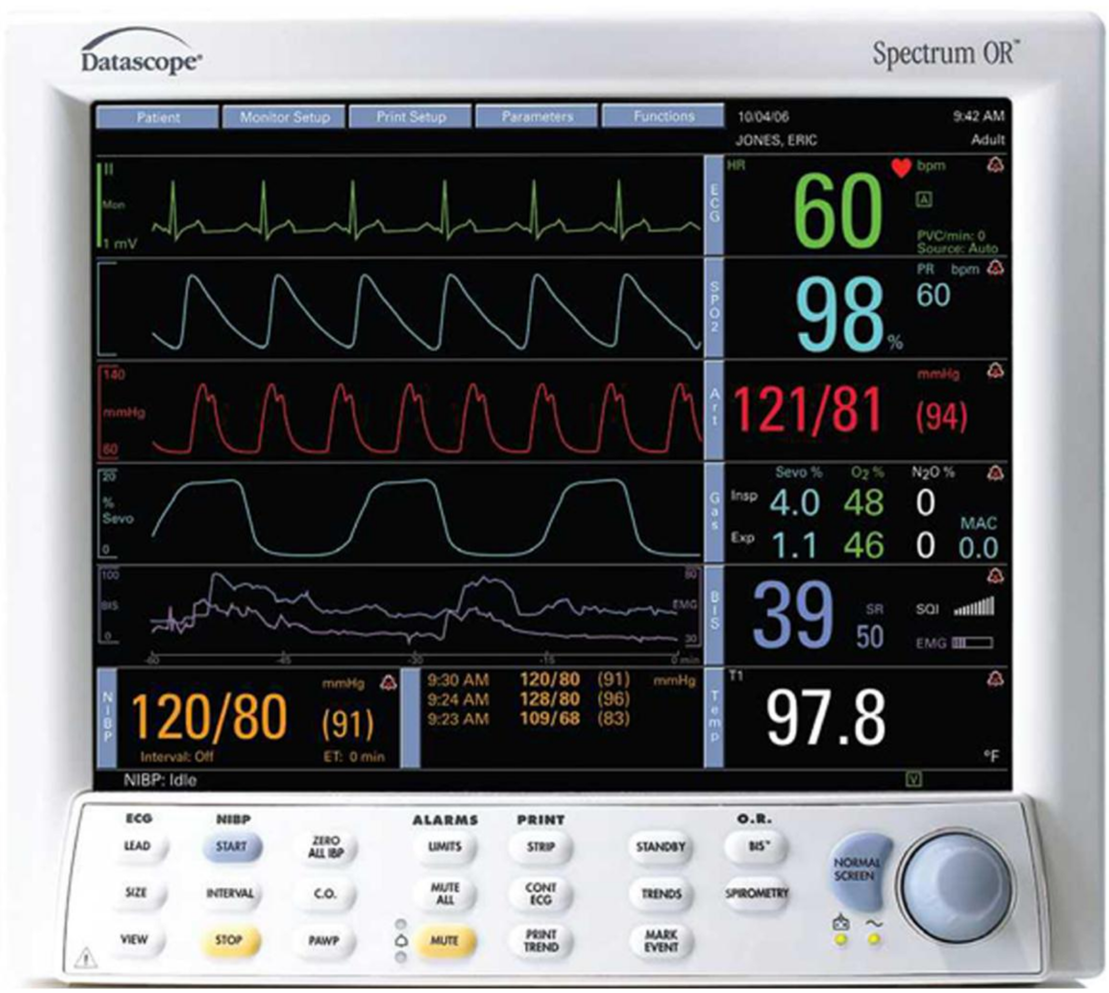


Figure 2. Traditional Anesthesia Monitor - one of the monitors used in the operating room that provides waveform and numerical values of patient physiological status.

For example, a capnogram (Figure 3), one of four to eight analog waveforms displayed on screen, is a real-time waveform record of carbon dioxide concentration in respiratory gases.

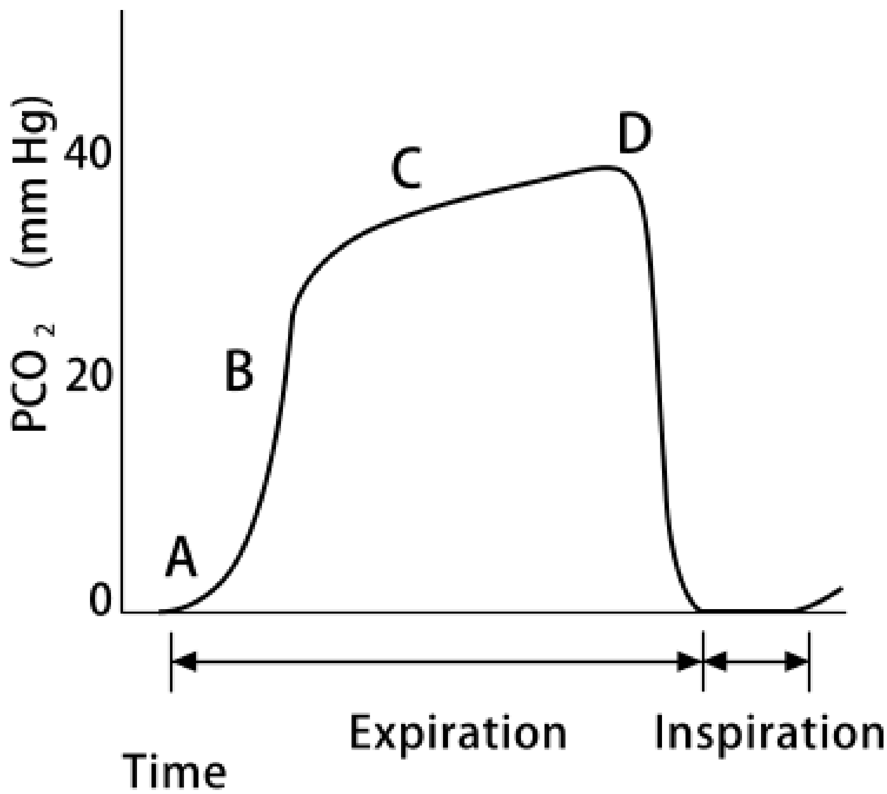


Figure 3. Capnogram indicating normal measures of carbon dioxide concentration (Dorland's Medical Dictionary for Health Consumers. © 2007 by Saunders, an imprint of Elsevier, Inc. All rights reserved.)

In the event of unusual physiological changes, such a capnogram would give indications to the anesthetists that patient conditions are unstable. In the case of Bronchospasm, for instance, in which the patient's airways are constricted as a result of sudden muscle constriction of the bronchioles walls, a capnograph (Figure 4) would present changes to the normal waveform.

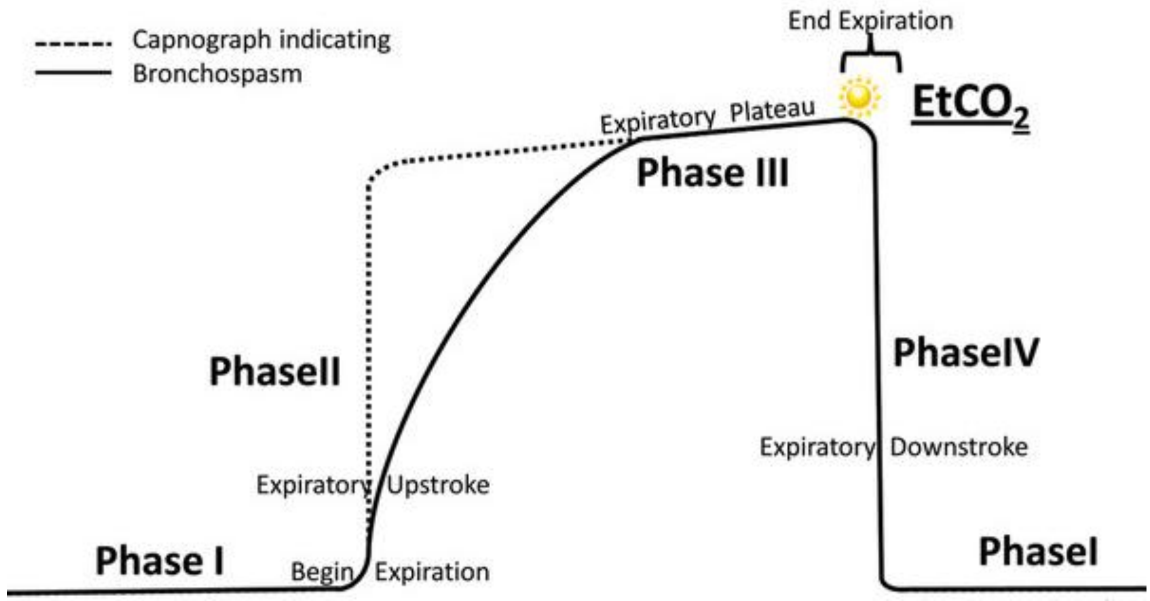


Figure 4 Capnograph indicating Bronchospasm (EMSWorld Magazine. © 2013 by Cygnus Business Media. All rights reserved.)

What the anesthetists ultimately face are rows of instantaneously updating waveform indicators that continually scrolls off old waveforms. Detection of any changes, which more or less relies on the comparison of old and new data, may not be immediate. As shown (Figure 5), visual changes in waveforms appear at a glance to be so minute that they may be difficult to detect, even when accompanied with numerical changes. Yet, timely waveform discrimination of various patient physiological changes is critical to developing anesthetic situation awareness.

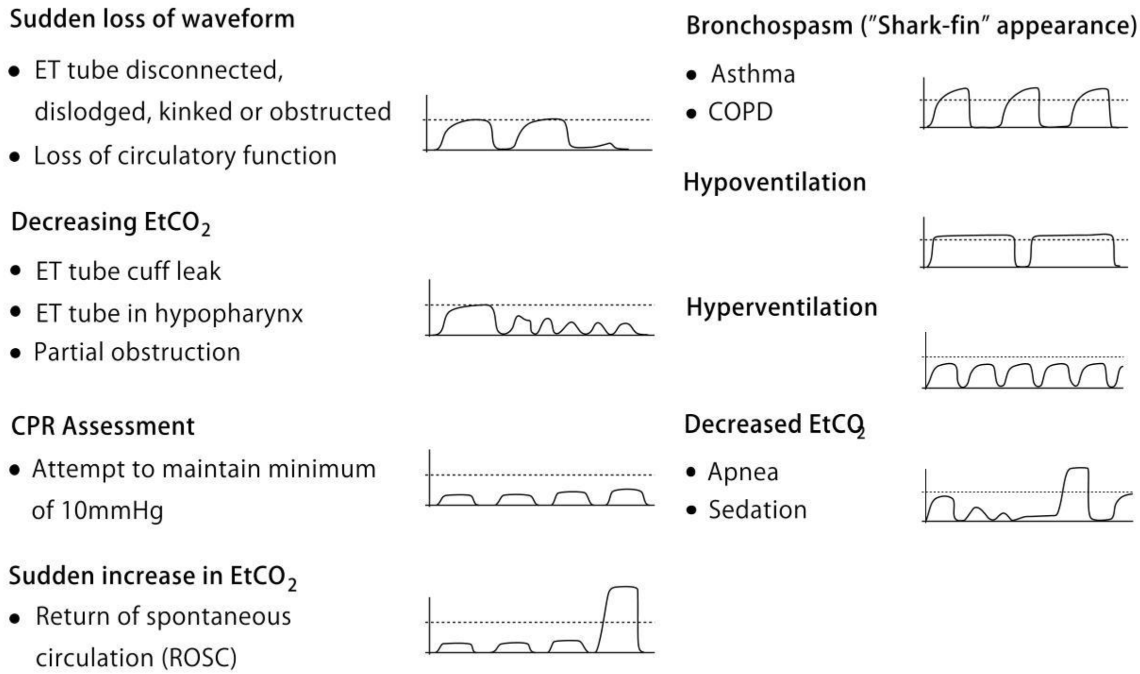


Figure 5. Capnographs waveform examples (EMSWorld Magazine.)

Situation Awareness

Situation awareness (SA), a concept traditionally conceived in aircraft flight management involving the need for comprehensive environment-specific awareness, is critical to achieving a state of readiness in anesthetic crisis management. It consists of three main levels of cognition "**perception** (level 1 SA), **comprehension** (level 2 SA), and **prediction** (level 3 SA)" [Lee, 2009, p. 1796]. For anesthetists to develop and maintain adequate SA, a continual knowledge update of the patient physiological state is crucial. Within the information-intensive anesthetic domain, practitioners often face different phases of information flow and data density punctuated by unpredictable periods of critical events. In effect, the task of anesthetic physiological monitoring is such that non-technical competence, rather than technical know-how, is a necessary precondition for proper patient care. Defined as 'the cognitive, social, and personal resource skills" [Flin, 2008, p.1], non-technical expertise determines how well anesthetists allocate visual resources for managing adequate SA objectives within the complex, stressful, and rather demanding environment of the operating room.

Attention

As attention is necessary to visual **perception** (level 1 SA), data displays that provide information alone may not be sufficient to attract user focus. This requires data salience, in which case, user-interface designers would benefit from capitalizing on the innate human behavior and perceptual mechanism underlying the concept of "affordance"—that which refers to the "behaviors…'afforded' by specific information layouts" [Strong, 1991, p. 220]. Affordances have been employed in architecture to encourage or discourage use of space by virtue of making available certain behavioral options in landscaping design. In much the same way, affordances could be applied to data display representations to achieve attention pull. This facilitates the "early perception [of]…select[ing] a subset of information from the enormous amount [of data] available" [Strong, 1991, p. 219] and deliberately channels it towards relevant input. Given that human visual capacity could only devote attention to a small amount of visual input at any one time, when subjected to such visual and behavioral constraints, perceptual processing is guided through the data maze and attention pull is more easily achieved.

Vigilance

For sustained attention, clinicians must be kept engaged. Such vigilance is necessary for the timely detection of unpredictable and infrequent stimuli from non-routine events (NRE).

Characterized as the “dysfunctional clinical system attributes or potentially dangerous conditions” [Weinger, 2002, p. S58], these events may escape notice should the anesthetist fail to maintain mental alertness. Data displays that do not effectively discriminate atypical signals from neutral ones tend to degrade user performance as they lack the prerequisite visual cueing features critical for highlighting relevant data values. Without such visual prompting, the cognitively taxed anesthetist—whose attention is vulnerable to distractions on account of other competing operating room activities—cannot be expected to respond promptly, much less execute an informed decision. Adequate **comprehension** (level 2 SA) is here compromised as anesthetists become susceptible to “change blindness” [Rensink, 1997, p. 368], a rather counterintuitive notion that involves the failure of human perception to detect “large changes that normally would be noticed easily” [Simons, 2005, p. 16]. Apparently, in the absence of attention fixation, changes to the visual field may not be perceived, especially if this just so happens to occur at the time of an eye movement. Such blindness holds true regardless of data change salience. This suggests that human perception is highly dynamic and heavily dictated by the visual needs and interests of the cognitive task at hand.

Decision Making

For informed task execution, users should receive support not only for data acquisition and integration, but also high level data projections. Data alone are rather useless without the proper contextual **prediction** (level 3 SA). As evidence illustrates, “even highly skilled professionals may act incorrectly because they have constructed an erroneous map” [Gaba, 1987, p. 673] rather than having acted erroneously. Independent of anesthetic experience, time constraints among other factors compromise anesthetists’ ability to properly visualize a situation without being cognitively biased. For this reason, user interfaces should structure data such that it produces emergent information relevant to the task, information that is not displayed but emerges from the mutual influence of data components. Such a design strategy should allow for a more comprehensive and objective analysis, thereby providing better visual support for generating hypotheses and establishing subsequent decision making. The following theoretical framework is based on the cognitive processes underlying such decision making, collectively defined under the umbrella term of situation awareness (SA).

Chapter 3

THEORETICAL FRAMEWORK/METHODOLOGY

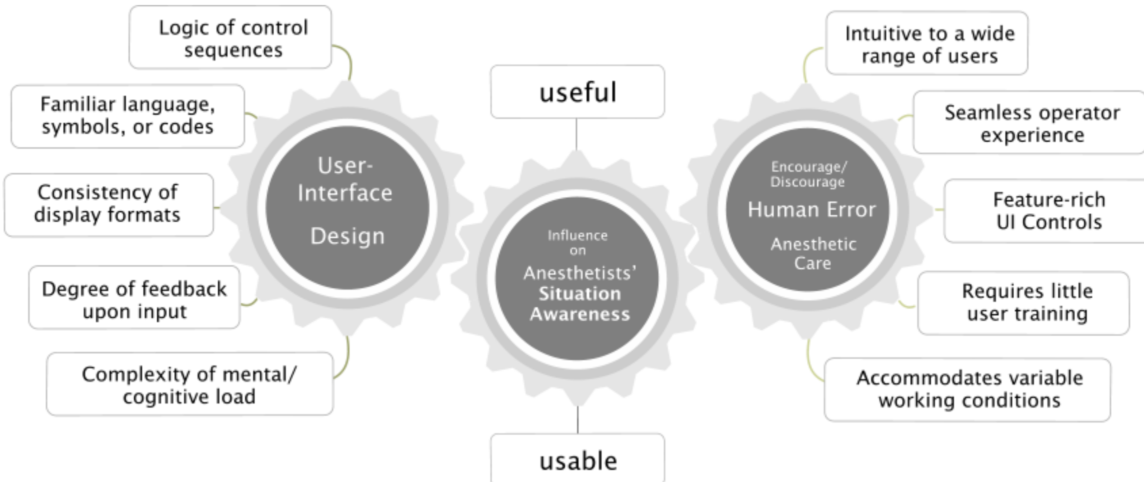


Figure 6. Theoretical Framework - assessing situation awareness (SA) within the context of anesthesia practice.

The theoretical framework (Figure 6) for this study reflects the aforementioned cognitive levels of situation awareness (SA) with an emphasis on the relationship of mutual influence between dependent variables: user-interface design and anesthetists' performance. Applied to anesthetic practice, the measures of SA involve assessing the ability of the anesthesia providers to maintain a state of readiness in a dynamic environment characterized by contradictory artifacts and complexity of data while using the medical care tools available to them, specifically the data displays. The framework focuses on the user-interface more so than the user as it evaluates both the particulars of 'usable' and 'useful' qualities of design elements that together, may function as decision inhibitors or enablers. As SA changes in response to environmental influences, the adaptive nature of user-interfaces in the evolving chain of clinical events is key to facilitating problem-solving and subsequent decision making.

Chapter 4

METHODS

A broad comprehensive search of published works pertaining to anesthetic physiologic monitoring was conducted beginning with the year 1970 when monitoring displays were first introduced into intensive care. This was achieved primarily via PubMed (a database containing science and chemistry journals), Academic Search Premier (containing scholarly publications), JSTOR (consisting of selected journals from the humanities and social sciences), and PsycINFO (includes literature in psychology and related disciplines). Search terms (found in the Appendix A) yielded a few thousand references, which were refined using the following general criteria of relevance: (a) anesthesia monitoring performance (b) physiological display evaluation, and (c) academic studies. This uncovered 65 articles that investigated user-interface design and human cognition in detail i.e. perception, attention, vigilance, workload etc. as well as various features and uses of physiological displays. Excluded from the search results were editorials, reviews, and general opinion pieces. A total of 37 empirical studies (including a study discovered by chance dated 1962 which was included on the basis of relevance) were identified of which 20 were extracted as they were directly tied to the use of data displays within the anesthetic context.

The studies were grouped into two broad classes: Monitoring (with primary focus on the user workload) and Monitors (with a focus on user-interfaces). The particulars of the studies were noted and fitted into a list for comparisons between categories i.e. study samples, designs, variables, and results. An in depth analysis of the studies was then conducted to identify highly relevant factors that may have contributed to the results of the studies, as shown in the following Tables 1a-c and Tables 2a-f:

Table 1a

Monitoring - a comparison between studies with a focus on user workload

	SAMPLE	DESIGN	VARIABLES	RESULTS	Contributing Factors Identified
Pfeffer *et al.* (2012)	Anesthetist (on site)	Comparison between pupil diameter values regarding anesthetic mental load Tasks: 2 surgical interventions and 1 exploratory laparotomy	Pupil diameter Scan path	Waveforms viewed first before numeric values were observed Widening of pupil in response to incoming warning signals	· **needs of tasks at hand**
Segall *et al.* (2007)	3 Anesthesio-logy residents (2nd yr) 2 Anesthesio-logists (5-20yrs experience)	Comparison between two groups of subjects regarding visual regions of interest (ROIs) Tasks: gauge patient state during simulated anesthetic induction	Visual patterns of fixations Gaze paths	More fixations before intubation—more interest in patient status due to airway concerns	· **requirements associated with particular phase of surgery**
Adams (1962)	12 University males undergrads	Comparison between visual loads regarding the impact on vigilance Task: monitoring over a 3hr session, for 9 consecutive days requiring change detectin; 7 days rest followed by 1 last session	Detection latency Response time	Minor trend of increasing decrement as time progresses Scanning behavior reduces in efficiency as observation time progresses Abandons orderly scanning of all display elements as time progresses	· **spatial configuration of stimulus sources**

Table 1b
Monitoring - a comparison between studies with a focus on <u>user workload</u>

	SAMPLE	DESIGN	VARIABLES	RESULTS	Contributing Factors Identified
Smith *et al.* (2003)	Anesthetists (on site at two general hospitals in England)	Comparison within and between subjects regarding critical incidents and personal practice Tasks: answer interview questions during or after operating sessions of different types of surgery	Monitoring approaches	Frequently faced with monitoring abnormalities Alarms repeatedly silenced Changes in monitor readings often prove groundless Mistrust of monitor readings	· **variability between patients** **instances of misleading abnormal readings**
Wright and Fallacaro (2011)	111 student re-gistered nurse anesthetists (SRNAs) from 3 large US universities	Comparison within subjects re-garding situation awareness Tasks: keep a crossbar in a moving circle target to engage an autopilot mechanism then complete a series of cognitively challenging bonus activities while keeping watch of autopilot; reengage autopilot upon spontaneous disengagement	Memory Automacity Cognition Change detection	Cognition best predicts SA Memory and Automacity contribute no additional predictive value	· **pattern matching** · **conscious analysis** · **make sense**

Table 1c
Monitoring - a comparison between studies with a focus on user workload

	SAMPLE	DESIGN	VARIABLES	RESULTS	Contributing Factors Identified
Drews and Lorimer (2008)	26 Intensive Care Unit (ICU) nurses	Comparison within subjects regarding usability issues with standard monitors via semi-structured interviews; a redesigned display is developed for further testing Tasks: answer interview questions for approx. 1hr	Monitoring using traditional displays Usability	Difficult data acquisition and processing of physiological parameters; piecemeal data gathering High frequency of false alarms Little adjustability of alarm thresholds Complex, counterintuitive menu Data clutter, small font sizes, and structure inconsistency	**lack of:** **· flexibility/ customization/ consistency** **· information integration** **· holistic/visual data trends** **· graphical representations**
John *et al.* (1997)	17 scientists, computer programmers, and administrators	Comparison between two monitors regarding effects of simultaneous tasks Tasks: perform task in one window, be interrupted and required to access another window to perform new task	Multiple monitor display Reaction time Disruptions	Moving task to a second display did not disrupt performance Reaction time was as fast on one monitor as the other	**· task requires little monitoring** **· periodic monitoring**
Sanderson *et al.* (1999)	18 Swinburne University members	Comparison within subjects with all displays Task: monitor 2 same displays and detect failure; press left if failure occurred to the left of screen, right if occurred to the right	Shape display Bar graph display Digital display	Shape display showing the highest scores of low prefontrol excitation Well-mapped versions show less prefrontal activity Poorly-mapped displays invoke prefrontal excitation and some lateralization	**· shape-mapping/ coding of information**

Table 2a

Monitors - a comparison between studies with a focus on user-interfaces

	SAMPLE	DESIGN	VARIABLES	RESULTS	Contributing Factors Identified
Dryer and Stanney (1998)	24 University of Central Floriad undergraduate engineering students between the ages of 17-30 yrs old	Comparison between subjects regarding information integration between two categories (i.e. either groceries and entertainment or clothing and luxury) Tasks: 6 tasks of involving budget categories (i.e. groceries, clothing, entertainment, and luxury) and two subcategories (i.e., consumable and nonconsumable)	3D displays vs 2D bar graph Focused attention Integration of data Performance time	Enhanced performance for both focused cattention and integrated tasks with curvatuve and gap displays	**· graphics** **· visuals** **· lines** **· curvatures** **· element orientation** **· contrast**
Michels *et al.* (1997)	2 groups of 5 anesthesio-logists	Comparison between 2 groups of subjects regarding signal change detection Tasks: observe 4 critical incidents; one group observing prototype display, another group viewed standard digital and waveform display	Prototype display vs traditional Reaction time Detection accuracy	Change detection was achieved 2.4 mins sooner with the prototype display than traditional display	**· shapes** **· colored figures** **· shape height proportional to volume**
Tappan *et al.* (2009)	22 anesthesio-logists	Comparison between subjects regarding visual display change detection Tasks: 6 simulated operating room scenarios; all use both standard anesthesia display and the enhanced display	Enhanced display vs traditional Response time Detection Accuracy Usability	Correct reason for detection identified 2.8 mins sooner with the ptototype Change detection was reduced by 14.4s using the enhanced display	**· visual cues** **· trends** **· probabilistic estimates**

Table 2b

Monitors - a comparison between studies with a focus on user-interfaces

	SAMPLE	DESIGN	VARIABLES	RESULTS	Contributing Factors Identified
Wachter *et al.* (2003)	22 anesthesio-logists, 1 nurse anesthetists, 18 residents, and 5 medical students	Comparison within subjects regarding responses to 7 iterative usability display designs via a three-step paper-based testing protocol Tasks: identify the anatomic, physiologic, and graphical meaning of the display from a predeter-mined set of choices	Graphical display vs traditional Intuitiveness Diagnosis support Color Association of display element with underlying tended representation	Designs 1-4 were not sufficiently intuitive Designs 5-7 were more intuitive, improved diagnostic accuracy, enforced element associations with colors	· **anatomically recognizable shapes** · **emergent features**
Jungk *et al.* (1999)	20 anesthesio-logists with varying years of working experience	Comparison within subjects regarding decision making via eye-tracking, event-logging, and think aloud protocol Tasks: control and monitoring activities	Experience/age Ecological display vs Profilogram display vs Traditional display Scan paths Behavior	No significant or important correlations between experience/age and problem solving 13% failed to achieve task goal with ecological display, 19% with profilogram display, and 37% with traditional Ecological display induced more regular scan patterns and strategic decision finding	· **visualized parameter in-terrelationships** · **visualized all task- and goal-relevant data** · **maps relational invariants** · **symbolic representation**

Table 2c

Monitors - a comparison between studies with a focus on user-interfaces

	SAMPLE	DESIGN	VARIABLES	RESULTS	Contributing Factors Identified
Jungk (2000)	16 anesthetists (14 males, 2 females; age: 32.4 ± 2.6yrs; working experience: 3.5 ± 1.9yrs)	Comparison within subjects regarding monitoring behavior, information-receiving and decision-making process via eye tracking, recording of subject's field of view and think-aloud protocol Tasks: administer 2 simulated general anesthetics with simulator's monitors alone and in combination with the ecological interface; identify 1 unexpected critical incident	Ecological display and traditional vs Ecological alone	Only 7 of the 15 subjects used traditional when ecological display was available Frequent fixations towards the alarm star and the alarmed regions of the ecological display Ecological interace used as main source of data Identified critical incident significantly faster with ecological interface	· **shapes are color-coded** · **outputs visualized as bars, squares, and stars** · **schematic work diagram**
Charabati (2009)	10 staff members and 10 residents/ fellows (15 males and 4 females)	Comparison within subjects regarding user performance and ease of critical event detection via video recording and questionnaires Tasks: identify one or more abnormal variables during five scenarios (simple and complex) for each display used and rate the workload	Numerical vs Numerical and graphical vs Graphical Reaction time Response accuracy Task load	Reaction times significantly shorter with mixed numerical-graphical interface Correct response rate was significantly lower with graphical interface Mixed numerical-graphical interace yielded significantly lower task load	· **composite representation of variables** · **horizonal bar graph, color-coded** · **trends given in curves and bi-dimensional graph**

Table 2d

Monitors - a comparison between studies with a focus on user-interfaces

	SAMPLE	DESIGN	VARIABLES	RESULTS	Contributing Factors Identified
Hu *et al.* (1999)	715 Business-major college freshmen	Comparison within subjects regarding information processing and retrieval Tasks: perform and review six information search tasks with each task involving a particular interface design; indicate perceived relevance of system-suggested items and interface cognitive load	4 Graphical vs 2 List-based displays Size Distance Color User satis-faction	Graphical interfaces provide significantly better system-sugested items than list-based interfaces Graphical interfaces using com-bination of size, disnace, and color were more effective in supporting system-user concept communication Size was the most effective in supporting concept communi-cation while disance was more effective than color in supporting communication Higher level of user satisfaction with graphical interface ing communication	· **size** · **distance** · **color** · **rich visual cues** · **system-suggested items**
Denault (1990)	6 Anesthesio-logists	Comparison within subjects regarding information processing Tasks: view 5 previously generated spreadsheet data files containing 6 columns of simulated physiological parameters presented in 2 display formats; detect critical event	Glyph display vs Traditional Reaction times	Glyph/polygon display proves significantly better in one abnormal data file according to reaction time in detection tasks Glyph/polygon display was favored by all participants	· **geometric measures** · **shape distortions** · **thick/thin lines** · **color-coded segments**

Table 2e

Monitors - a comparison between studies with a focus on user-interfaces

	SAMPLE	DESIGN	VARIABLES	RESULTS	Contributing Factors Identified
Blike *et al.* (2000)	7 anesthesiologists	Comparisons between display formats regarding impact of displays on performance Tasks: 2 diagnostic tasks requiring 10 diagnostic decisions regarding patient state using one display; another 10 decisions using other display	Object displays vs traditional Problem state recognition Problem etiology determination	Problem states are recognized faster and more accurately with object displays (both with and without shapes) compared to traditional	· **shapes** · **emergent features** · **shape-encoded data** · **pointers** · **bars** · **reference scale**
Confer and Hollands (1999)	32 University of Idaho undergrads	Comparisons between display types regarding impact on cognitive styles Tasks: focused and integrated tasks with the order of the tasks being randomized	Configural display vs. traditional Response time Accuracy	Shorter response times for both types of tasks with configural displays than non-configural displays	· **emergent features**
Spence *et al.* (1999)	20 undergrads	Comparisons between subjects regarding effectiveness of various color coding schemes Tasks (experiment 1): perform simple tasks, such as direct estimation with artificially constructed data sets, both systematic and random	4 Displays: contour, mosaic, random contour, and random mosaic Reponse latency and accuracy Brightness, Hue+Saturation+Brightness, Bipolar, Hue-only	Brightness scale led to significantly fastest response times Hue with saturation and brightness led to the most accurate responses Bipolar and Hue-only produced more errors	· **spatial meaning** · **color-coded data** · **scale** · **element distance**

Table 2f
Monitors - a comparison between studies with a focus on user-interfaces

	SAMPLE	DESIGN	VARIABLES	RESULTS	Contributing Factors Identified
cont. Spence *et al.* (1999)	20 psychology undergrads	Tasks (experiment 2): perform complex tasks, such as cluster detection with artificially constructed data sets, both systematic and random	4 Displays: contour, mosaic, random contour, and random mosaic Reponse latency and accuracy Brightness, Hue+Saturation +Brightness, Bipolar, Hue-only	Hue+Saturation+Brightness sacle produced fastest response time, bollowed by biplar scale, brightness cale, and hue-only scale Required least amount of processing time with contour display and mosaic display Random data display (random clustering) produced poorer and slower performance Well-defined data structure enhances speed and accuracy of cluster detection	· **spatial structure** · **coding scheme** · **multiple hue scale** · **color for data segregration and separation**

Chapter 5

FINDINGS

Themes emerged from the systematic assessment of the empirical studies listed in the previous Tables 1a-c and Tables 2a-f that define the function of contributing factors identified in the studies.

Monitoring – User Workload (Tables 1a-c)

Three main themes emerged (Table 3a) from the list of studies that provide insights into the nature of anesthetic monitoring in general and the needs of anesthetists specifically: Circumstantial Influences, Monitoring Tasks, and Monitor Needs. Circumstantial influences consist of factors that appear to dictate anesthetic monitoring such as the phase of surgery, the variability between patients, the needs of the tasks at hand, and the spatial configuration of the data sources. These factors should be taken into account in interface design as they may require data displays to have a built in degree of flexibility to accommodate various situations. The Monitoring Tasks of the anesthetists include periodic monitoring, conscious analysis, information integration, abnormal readings, pattern matching, and sense making. These seem to require and involved level of mental and visual effort on the part of the anesthetist. They call for their full attention, vigilance, and accurate/prompt decision-making. Not surprisingly then, the Monitor Needs of the anesthetists are found to consist of graphical representations, flexibility/customization/consistency, holistic/visual data trends, and shape-mapping/coding of information. Interestingly, these factors fall under both usable and useful, requiring monitors to not only incorporate ease of use but also function usefully with regards to data integration and projection.

Table 3a

Themes that emerged from studies on monitoring - reveal influencing factors, tasks, and user needs.

CIRCUMSTANTIAL INFLUENCES

Influences that dictate the act of anesthetic monitoring

particular phase of surgery	**variability between patients**	**needs of tasks at hand**	**spatial configuration of stimulus sources**

MONITORING TASKS

Tasks typically carried out during patient physiological monitoring

periodic monitoring	**conscious analysis**	**information integration**	**abnormal readings**	**pattern matching**	**make sense**

MONITOR NEEDS

Data needs of the anesthetists to be considered in monitor designs

USABLE		USEFUL	
graphical representations	**flexibility/ customization/ consistency**	**holistic/visual data trends**	**shape-mapping/ coding of information**

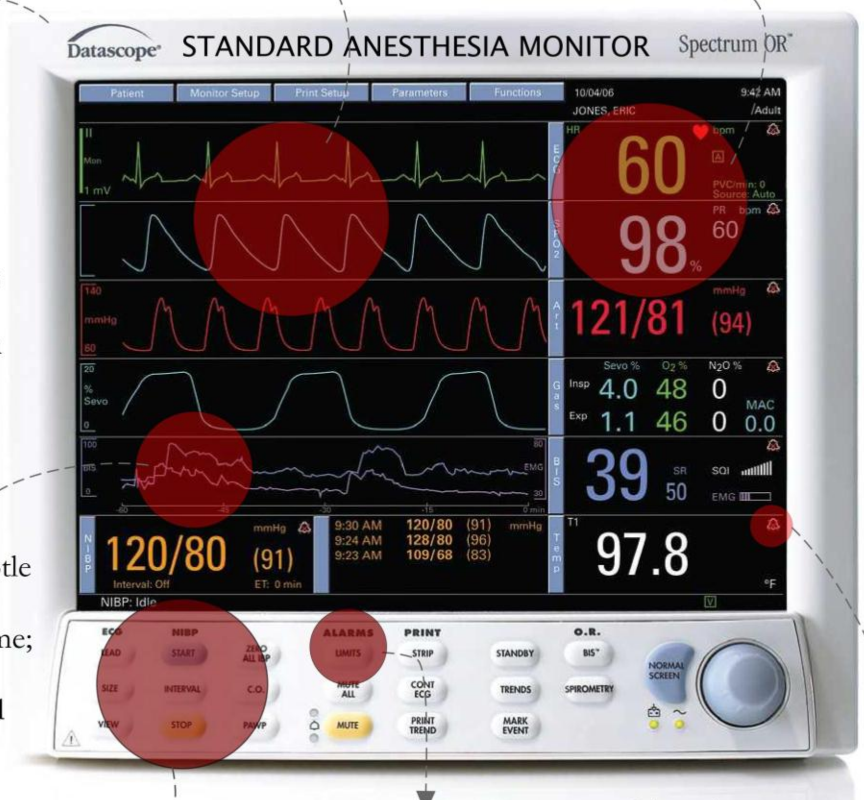
Monitor needs were revealed as a result of user performance shortcomings during the use of the present standard single-sensor-single-indicator (SSSI) patient physiological monitor. When these were combined with test subjects' talk-aloud-protocol, the limits of the SSSI were further confirmed. Apparently, the interface not only does no provide comprehensive, integrated data, its measures may actually be misleading, as shown in Table 3b.

Table 3b

Factors that emerged from studies on monitors - reveal shortcomings of traditional monitors.

waveforms may appear too similar; comparison is made difficult

numbers increasing create a sense of panic and anxiety as they do not provide additional information



values by themselves do not provide an adequate picture of the patients' status; these **values must be taken together and integrated for sense making**

sudden unforeseen subtle changes can occur at any time; there is **no obvious visual cues t**o draw attention to deviations from normal values

menu structure may not be intuitive with little to no customization

default **alarm limits may be inappropriate** for patients whose long-term drug treatment fall outside machine's normal ranges

false alarms are frequent and are often ignored at the expense of the case of positive alarms

Behavior forced on anesthesists as a result of their use of traditional monitors:

- frequent false alarms force anesthetists to **repeatedly silences alarms**, ignoring readings at the expense of true alarms
- subtle value deviations lead anesthetists to easily **miss anesthetic critical events**
- frequent misleading abnormal readings due to limited monitor definition of 'normal' range result in the general **mistrust of electronic signs**, which adds to anesthetists' mental workload as actual physical signs must be continually assessed and integrated
- unusual events mean a very small change somewhere in the overall numbers displayed but are not made transparent on the monitor, which cause **real panic and anxiety** and does not inspire confidence and control of the situation

Monitors – User-interfaces (Tables 2a-f)

Three main themes (Table 4) emerged from the list of studies focused on the monitors' user-interfaces reveal the essential qualities of effective data displays: Engaging, Meaningful, and Holistic.

Engaging data displays make generous use of rich visual attributes such as various shapes and figures combined with color, contrast, size, weight, orientation, distortions etc. that together *actively* cue the user and facilitate his/her visual engagement. Besides preventing tunnel vision, engaging data is necessary to develop proper perception of visual field input. Meaningful data displays encode extra relevant information into visual features to yield additional data depth and clarity. This is achieved with deliberate schemes such as color-coded data, spatial structure, anatomically recognizable shapes, or shapes that change in height proportionally to anesthetic volume etc. The resulting meaningful data representation enhances user awareness and aids in data comprehension. Holistic displays provide visualized parameter interrelationships, probabilistic estimates, trends, etc. that illustrate the mutual influence of data components, which provide the user with an overall, comprehensive view of information. Such metadata, or data about data, effectively shape user's judgment and decision making as it assists users in information projection and prediction.

Under each theme are visual examples that emerged from the studies to be one of the best representations of the each concept. The ways in which the graphics were incorporated are discussed in detail in Table 4b-d.

Table 4a

Themes that emerged from studies on monitors - reveal qualities for improved user-interface design.

ENGAGING Factors that produced engaging data to the user necessary for data **perception**.

visual cues	**size**	**contrast**	**element distance**
shapes	**curvatures**	**color**	**thick/thin lines**
outputs visualized as bars, squares, and stars	**orientation**	**graphics**	**reference scale**
	multiple hue scale	**pointers**	**shape distortions**
		scale	**colored figures**

MEANINGFUL Factors that produced meaningful information to the user necessary for data **comprehension**.

shapes are color-coded	**color-coded segments**	**color-coding scheme**	**element orientation**
horizonal bar graph, color-coded	**color-coded data**	**color-coded data segregration and separation**	**anatomically recognizable shapes**
geometric measures	**spatial meaning**	**system-suggested items**	**shape-encoded data**
shape height proportional to volume	**spatial structure**	**visualized all task- and goal-relevant data**	**schematic work diagram**
	emergent features		**maps relational invariants**

HOLISTIC Factors that produced holistic information for the user necessary for data **prediction**.

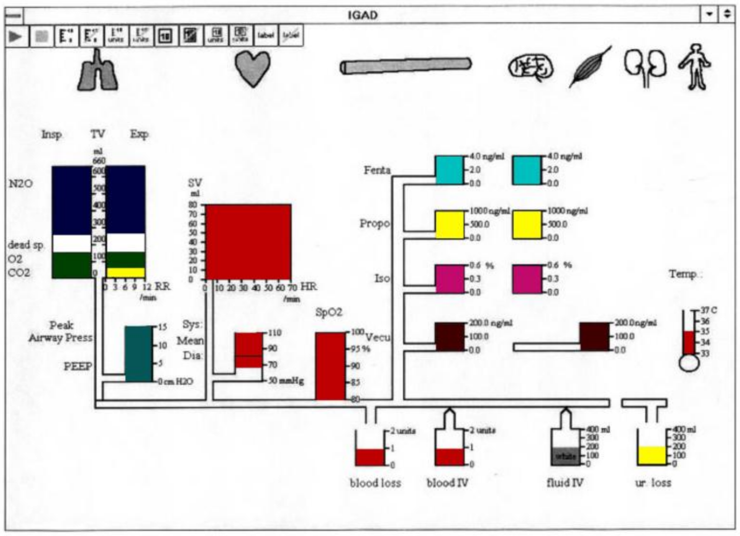
probabilistic estimates	**trends given in curves and bi-dimensional graph**	**visualized parameter interrelationships**
symbolic representation	**composite repre-sentation of variables**	

Table 4b

Examples that emerged from studies on monitors - reveal qualities for improved user-interface design.

ENGAGING examples

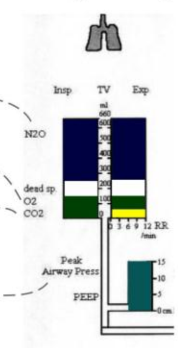
Examples that produced one of the most engaging information to the user necessary for data **perception**.



This graphical display from the Michels study provides an integrated, visually engaging graphic of 30 monitored variables organized according to function: Respiratory, Cardiovascular Drug Delivery, and Fluid Management

Source: Michels *et al.* (1997)

Respiratory



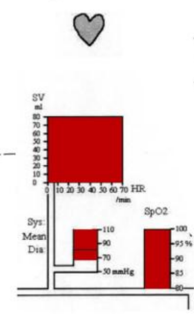
nitrous oxide

oxygen

carbon dioxide

peak airway pressure

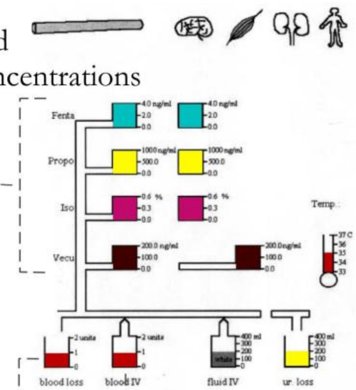
Cardiovascular Drug Delivery



cardiac output where stroke volume (SV) is plotted with heart rate (HR)

Fluid Management

blood and tissue concentrations



blood administered

urine loss

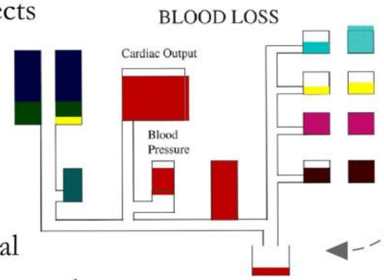
blood loss

IV fluid

Design advantages over traditional data displays:

- visual organization adds structure to data; directs and engages appropriate attention
- data changes correspond with shape changes
- all data is heavily visual
- variables have reference scales

Source: Michels *et al.* (1997)



blood loss

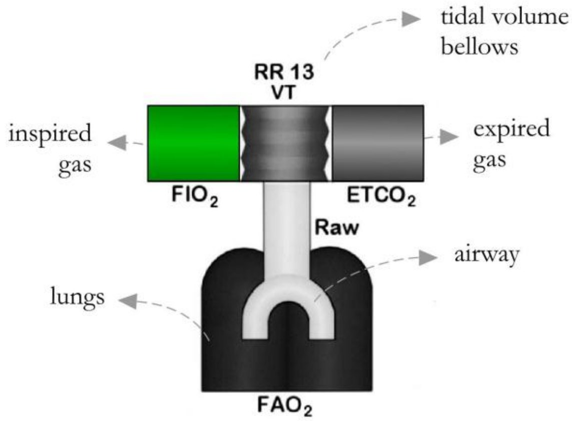
A simulated blood loss event would show a screen with colored shapes deviating from normal states, which visually maintains user engagement as the changes here are more discernable.

Table 4c

Examples that emerged from studies on monitors - reveal qualities for improved user-interface design.

MEANINGFUL examples

Examples that produced one of the most meaningful information to the user necessary for data **comprehension**.



Normal

Source: Wachter *et al.* (2003)

This graphical display from the Wachter study is intended to assess pulmonary events in anesthesia. It is designed to be **anatomically intuitive** for users and, of 7 iterative designs produced in the study, yielded the most optimal results for pulmonary diagosis.

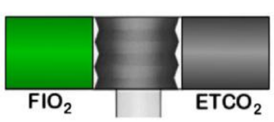
Design advantages over traditional data displays:

The accordian-shaped bellows expands vertically to represent changes to normal tidal volumes. This is intuitive and meaningful as it represents the actual bellows used in anesthesia ventilator machine.

The airway shape meaningfully mirrors the trachea and branched bronchi of the lungs.

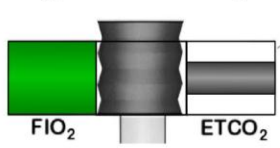
The form of the lungs are bisemielliptical, which aids in image recognition as lungs are typically this shape.

lungs



Standard operating colors were used i.e. green to indicate oxygen levels and gray to indicate exhaled CO_2.

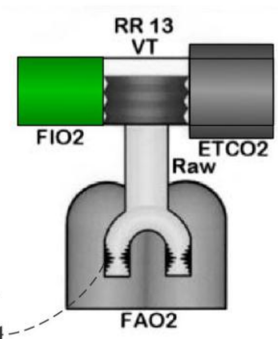
The **information is mapped** to the values such that, in this instance, colors expand or contract to indicate abnormality in values, which here denotes a hyper-ventilation pulmonary event.



outlined box functions effectively as a **reference frame**

Hyperventilation pulmonary event

system-suggested concept of the narrowing of two lower bronchi, which indicates obstruction in lower airways



Bronchospasm

Table 4d

Examples that emerged from studies on monitors - reveal qualities for improved user-interface design.

HOLISTIC examples — Examples that produced one of the most holistic information for the user necessary for data **prediction**.

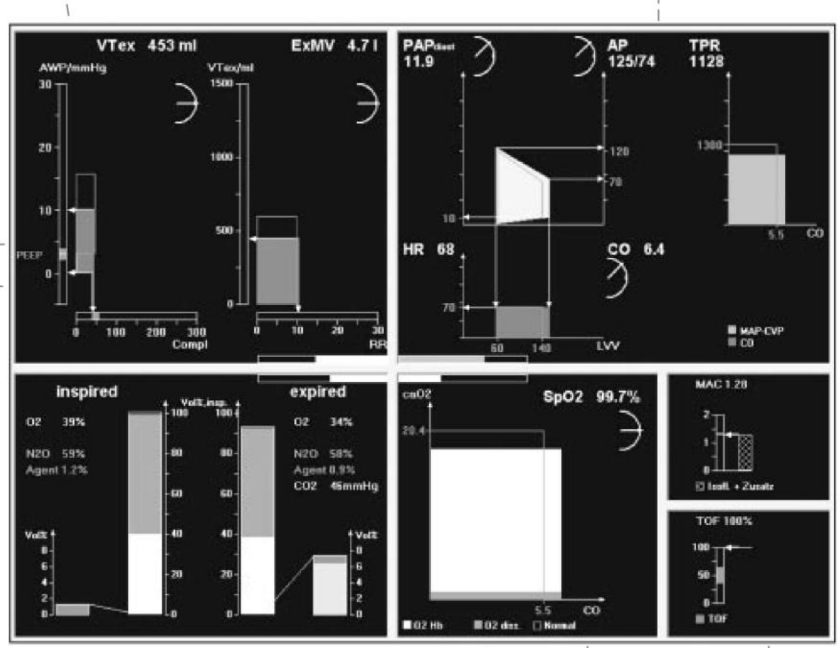
y-axis measures minimal airway pressure (AWP) **visualized as green bars**

cardiovascular system is **visualized using a schematic work diagram** of the heart with normal values marked on corresponding axes or displayed as green rectangles and **includes trend arrows** showing the last assessment of the last 90s-tend

respiratory mechanical paramters **visualized as a square** to indicate expired tidal volume (Vt_{ex})

x-axis measures airway compliance for spontaneous and controlled ventilation

inspired and expired tidal volumes in which the **height of the expired volume bar is provided in relation to the inspired volume**



Source: Jungk *et al.* (2000)

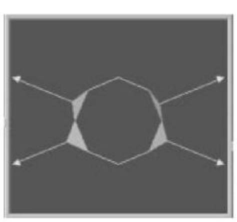
fluid management: infusion fluid, plasma administered, and urine output **expressed as bars**

pulse oximetry data SpO_2 **displayed separately to carry extra importance** with trend data

oxygen supply, visualized as a square, is determined by oxygen content in blood (y-axis) and cardiac output (x-axis); normal value is **included as reference**

anesthesia depth and relaxation level displayed **with clinically relevant parameters**

This graphical display from the Jungk study visualizes 35 variables, with all bars and squares **color-coded**, **organized on one screen according to their function and relationship** to each other to support anesthesia decision-making.



Displayed in the middle of the screen is this color-coded star that **represents an overall holistic assessment**, a parameter constellation of sorts, of the patient condition, **drawing from and mapping values** of respiratory mechanics, respiratory volumes, oxygen supply, and the cardiovascular system.

Discussion

Studies under Table 1a-c demonstrated that anesthetists have certain data display needs during patient physiological monitoring. The data provided on standard single-sensor-single-indicator (SSSI) patient physiological monitoring equipment does not adequately capture the actual state of the patient and his/her response to anesthesia. As they lack visual cues, they are designed for data availability rather than data extraction, which do not necessarily work in conjunction with the cognitive processing necessary problem-solving. As demonstrated in task analysis studies, to maintain SA, the anesthetist is invariably tasked with sequential data gathering of extracting, integrating, and interpreting patient physiological parameters, a rather time-consuming and inefficient allocation of cognitive resources. As there are no meaningful data trends provided on the interface, any unusual fluctuations in the monitored variables must additionally be overseen, recognized as abnormal, and swiftly attended to for prompt remedial action. Although in the course of data gathering, visual and audible alarms integrated into the monitoring displays do serve to call attention to that which the equipment deems as unusual events, false positives are rampant due to equipment sensitivity to patient movement and interference provide no clear problem signal to the user. As such, no system-suggested metadata or information about information is available to the practitioner and the overall clinical situation may not be properly communicated. Such findings are rather telling of the limited nature of clinical data monitors currently in use.

Studies under Tables 2a-f illustrate that observation tasks show significant sensitivity to visual shapes as they heavily impact change detection. The shape-coding of information facilitated subjects' reaction time, which is consistent with cognitive imaging studies in which displays with well-mapped information resulted in less prefrontal activity. Likewise, with decision tasks, subjects especially benefited from visual cues. This is evident in their ability to direct the subject's attention towards the problem states, leading to timely and accurate detection. The probabilistic trends of visual patterns also influenced reaction times as they enable data prediction.

The findings are consistent with the Situation Awareness paradigm of perception, comprehension, and prediction. That is, data displays that are oriented towards supporting these aspects of cognition are better able to enhance user SA. The systematic assessment of the empirical studies identified contributing factors that demonstrate visual attributes to be the most prominent feature impacting user performance.

Implications

User-interface display designs that take advantage of the rich visual attributes of graphical images to communicate dense information appear to better enhance user focused attention than do traditional displays. Visual shapes effectively function as attention grabbing stimuli that not only aid in sustaining attention but also in data decoding. As their individual components have mutual influence, emergent features are brought about with a pop-out effect that is readily perceived. Information salience is improved when displays pay attention to the use of color, scale, and line curvature. When compared to traditional displays they yield statistically significant results for integrated tasks. When faced with having to monitor and assess multiple data streams, digital cues that prioritize visual input facilitate early change detection and prompt corrective action.

Recommendations

To achieve adequate user situation awareness (SA) and facilitate decision-making, the user-interface designer should consider, first and foremost, the spatial organization of data on screen. Much like the visuals shown in Table 4b, groupings of similar data sets under clear, meaningful categories, in this case, i.e. Respiratory, Cardiovascular Drug Delivery, and Fluid Management, effectively structure visual input for the user and prevents haphazard, piecemeal data gathering from separate, disjointed data measures found in traditional waveform monitors. Shapes should be considered that are compelling and meaningful in their representation. As illustrated in Table 4c, these shapes are anatomically recognizable to the user, creating instant visual comprehension. Designers should take care to include a reference scale to accompany such shapes to function as normal states for the purposes of data comparisons to aid in prompt change detection. Changes in sizes could usefully indicate abnormal states and signal users towards recognition and action. Colors should be used sparingly as they require users to be absolutely without any color detection abnormalities. If used, designers must take into account color standards that users have habituated themselves to and maintain consistency in functionality to avoid confusion in color-coded data interpretation. Finally, all aspects of data structure, shapes, sizes, colors should have an obvious schematic relationship to each other. Providing users with the whole picture instead of separate numbers and figures help facilitate data integration and more importantly, data projection. Trends and probabilistic measures arising from emergent information, information not expressly displayed but arise from the mutual influence of other data, provide users with a composite, holistic view of the past and present situation such that users may, without much effort, produce useful hypotheses that aid in more accurate decision making.

Chapter 6

CONCLUSION

The findings confirm the research hypotheses that user-interface design influences the three cognitive levels of anesthetic SA and hence, anesthetic decision making. As such, user-interface designers must take care to acknowledge that data displays have the potential to help or harm, especially within anesthetic practice. How and to what users direct their perceptual and cognitive resources necessarily influence their perception of the environment, and by extension, their development of SA. Although patient monitoring equipment employed in anesthetic practice has proven to be indispensible in quality patient care, graphical representations of patient data is still far from optimal in the clinical setting. The standard single-sensor-single-indicator (SSSI) design require clinicians to mentally integrate and interpret multiple parameters to arrive at a comprehensive understanding of the patient's status—the correct assessment of which is a necessary precondition for appropriate anesthetic monitoring. This cognitively taxing process adds to the clinician's mental workload, which provides opportunity for errors in judgment and decision making.

There is a direct correlation between user-interface design and decision making. The SA required for decision making heavily relies upon data displays oriented towards information extraction and integration. The research data illustrate that when inundated with dense, competing information within complex, stressful environments such as the operating room, there is a temptation on the part of the operator to take cognitive shortcuts such that they become vulnerable to developing erroneous SA on account of the shortened, oversimplification of data. Adequate SA requires informed perception, comprehension, and projection of data. User-interfaces that lend decision support to facilitate SA and subsequent decision making are critical in medical error management.

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APPENDIX A

SEARCH TERM QUERIES

anaesthetic mishaps
patient physiological data displays
anaesthetic vigilance
human error
signal detection
mental workload
visual memory
user-interface
multi-tasking
attention span
situation awareness
visual memory
data perception
data detection
human computer interaction
multiple monitors
visual cues