Data Representation Architecture: Visualization Design Methods, Theory and Technology Applied to Anesthesiology

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Abstract

The explosive growth of scientific visualization in the past 10 years demonstrate a consistent and tacit agreement among scientists that visualization offers a better representation system for displaying complex data than traditional charting methods.

However, most visualization works have not been unable to exploit the full potential of visualization techniques. The reason may be that these attempts have been largely executed by scientists. While they have the technical skills for conducting research, they do not have the design background that would allow them to display data in easy to understand formats.

This paper presents the architectural methodology, theory, technology and products that are being employed in an ongoing multidisciplinary research in anesthesiology. The project's main goal is to develop a *new data representation technology to visualize physiologic information in real time.* Using physiologic data, 3-D objects are generated in digital space that represent physiologic changes within the body and show functional relationships that aid in the detection, diagnosis, and treatment of critical events.

Preliminary testing results show statistically significant reduction in detection times. The research outcome, potential, and recently received NIH grant supporting the team's scientific methods all point to the contributions that architecture may offer to the growing field of data visualization.

1 Background and Significance

In 1993, a report to the National Science Foundation (McConathy and Doyle 1993) stated that there was so much information being produced that all scientists could do was to find a place to warehouse it. The report concluded recommending visualization as the way to respond to this major challenge facing the sciences. The explosive growth of scientific visualization in the past 10 years has been a de-facto and clear validation of that report. There is now a consistent and tacit agreement among scientists that visualization offers a better representation system for organizing, studying (i.e., simulating, testing), using and communicating complex data. Case studies, Human Factors and Cognitive Sciences have shown that the human mind deals better with information complexity when data is displayed in graphic, real-world analog representations rather than in text-based or numerical representations (Adams et al 1995; Goettl et al 1991; Klima 1985; P1000 1996; Tufte 1997, 1990, 1983; Wurman 1996). Additional research in thinking, imagination, ideation, and learning has repeatedly shown that visualization plays a sophisticated and essential yet intuitive role in helping us associate, manipulate and infer information (Arnheim 1969, Egan and Nadaner 1988, Gardner 1983, Grinstein and Levkowitz 1995, McKim 1980).

These works suggest that effective data representation requires the presentation of information in a manner that is consistent with the perceptual, cognitive, and response-based mental representations of the user. When there is compatibility between the information presented to the user and the user's cognitive representations, performance is often more rapid, accurate and consistent. Conversely, a failure to use perceptual principles in the appropriate ways can lead to erroneous analysis of information. In other words, the way data is represented is of paramount importance as a means of augmenting human ability to make decisions while reducing stress and cognitive effort associated with them.

These findings lend strong support to the adoption of more qualitative methodologies in the design of data visualization systems. This, however, has not proved easy to implement. The reason is simple: most of the work on scientific visualization has been done by those who develop the data themselves: the scientists. Scientists have been largely trained in quantitative and not qualitative methods, in analytical and not integrative processes, in obtaining and not communicating knowledge. And yet, scientists find themselves with the growing pressure of communicating or just making sense out of increasingly more abstract data in ever larger amounts collected by ever more complex instruments.

The problem significantly escalates when dealing with *processes* as their study demand the monitoring of large data sets changing *in real time*. In addition to ordinary visualization requirements, representations depicting processes in real time call for difficult data management and display design techniques to assure the rapid discrimination of relevant information. The fact that the parameters normally used to monitor processes (e.g., temperature, pressure, rhythms, radiation, electromagnetism, etc.) are non-spatial does not make things any easier. Non-spatial numeric data create an apparent block in people's ability to represent them in any way other than in obvious mathematical space (i.e., function graphics such as 2D plots, pie charts, wave-form, etc.). Hence, despite some advances in Aviation and Process Control, disciplines such as the Physical Sciences, Finance, and Engineering are still using data visualization techniques of the pre-digital era to display data in real time.

This situation is evident in Medicine. Most of the work in medical visualization falls into three camps: (1) still imaging (e.g., X-rays, CAT scans, etc.), (2) interactive, but *not* real time, modeling of the body (MacLeod and Johnson 1993), and lately (3) interactive and real time dynamic representation of anatomic parts (for instance see Metaxas 1996). Little or no work has hitherto focused in visualizing ***processes and states*** (i.e., body function or physiology) instead of ***organic structures*** (i.e., body's forms —anatomy). This is remarkable given the relevance and power of *real time visualization of metabolic data in medical diagnosis*.

Recent research conducted in ***anesthesiology*** give clear evidence that visualization of physiological conditions offers faster and more accurate interpretations of medical data than the current numerical or wave-form representations, implying greater safety, decreased professional stress, and increased performance in patient monitoring (Cole and Stewart 1993, Deneault et al 1991, Gurushanthaiah et al 1995, Michels and Westenskow 1996, Michels et al 1997).

This paper reports on an interdisciplinary research project dealing with this undeveloped area of medical imaging: ***the visualization of physiologic data***. The goal is to create a new visualization model and technology for physiologic change based on:

- a new ***formal semiotics*** using basic principles, elements and systems of graphic depiction. This implies the development of graphic conventions to make possible the translation and understanding between numerical parameters and images or shapes.
- ***data integration***; the design of a multimodal virtual environment that expresses relationships among separate sets of measured data may not only reveal critical states more effi-

ciently and quickly than isolated representations, but also point at conditions that may not be apparent in separate displays of data.

- ***interactivity***; the new model needs to allow the user to dynamically work with the data through diverse hierarchical layers, hyper-representations, and various multimodal formats. Easy and natural interface with data supports better understanding of the ongoing situation and improves performance.

Developing a visualization model that incorporates these three design premises would revolutionize the way the medical field detects, diagnoses and treats physiologic conditions. Traditional displays are characterized by numerical-waveform (as opposed to geometrically graphic), discrete (as opposed to integrated), and non-interactive data representations (see Figure 1).

Figure 1. Current display of physiologic data (Hewlett Packard, Rockville, MD)

Designing a visualization system for displaying physiologic data in real time implies significant computing challenges. The problem of visually displaying multiple data sets —which turn out to be of large size because of the evolution in time at high frequency— demand fast computations to guarantee the complete full cycle of data input, computation, visualization and interactivity within instants. Research in real time integrated 3-D visualization for representing multiple non-spatial time dependent data is still at primitive stages or unpublished (Farley et al 1993, Fuchs et al 1989, Gobel 1996, Gunther et al 1995, Jablonowski et al 1993, McCormick et al 1987, Mihalisin et al 1991, Rosenblum 1994, Sillion et al 1997). Studies of integrated information systems are being actively pursued in fields such as Process Control, Aviation, Telecommunication, and Defense. For obvious reasons of security or protection from competition, research in this area is not disseminated. Hence, an important goal of our visualization design research was not only to significantly enhance medical decision-making but also advance public knowledge and discussion in the field of real time process visualization.

2 Relevance of Architectural Design in Medical Visualization

The importance of Architecture in the design of a data visualization system for Medicine cannot be overstated. Main stream medical visualization basically means to ***enhance*** a given set of anatomic images or behaviors so that they become more readable or act more accurately. In this type of work there is minimal need for design considerations because organic structures already possess their own characteristic shapes and movements. In contrast, physiologic data have no particular form and therefore demand the creation of representations. Numerical parameters (e.g., a blood pressure reading of 120/80, a heart rate of 70/minute, etc.) have no spatial or graphic imperative except in plots or charts constructed in mathematical space. This research work therefore deals with the ***invention*** *(not just the enhancement) of visualizations*. It clearly requires expertise in the area of visual design.

The importance of architectural design in the representation of physiologic data is also manifested by considerations such as

- the malleability of the digital canvas. Electronic space is neutral, in the sense that it may support any kind of representation design and format. This dimension refers to *formal aspects* of data representation design.
- communication demands. The data has particular meaning that needs communication (i.e., message) while the audience has particular ways to read and react to representations. This dimension refers to *functional and contextual aspects* of data representation design
- instrumental constraints. Hardware and software have inherent limitations to process complex dynamic databases that demand careful considerations at the time of visualization design. This dimension refers to the *economic aspects* of data representation design.

In other words, designing a new visualization system requires decisions about what information should be left out, highlighted or contextualized and how it should be represented. It is this essentially *qualitative filtering and visual depiction of information towards achieving a clear end that constitutes data visualization design.*

It is the design expertise in formal semiotics that makes architecture so relevant to this visualization research effort. Architects ordinarily deal with the syntax, semantics, and pragmatics of abstract 2D and 3D geometry. As a result the discipline has collected a comprehensive knowledge base of the nature, methods, and value of basic (i.e., abstract, geometrical) 2D and 3D design and its relationship to human collective and individual psychology and behavior (Albers 1975, Arheim 1977, Bloomer 1976, Broadbent et al 1980, Ciocier 1993, De Sausmarez 1964, Osgood et al 1957, Porter 1979, Wong 1977, 1972, Zettl 1973). This specialty area has been appropriately termed “Basic Design” and its theories, understandings, and methodologies are shared among all design disciplines (i.e., industrial design, graphic design, interior design, media design) and have a strong relationship with cognitive and environmental psychology. This knowledge base consisting of basic principles (e.g., scale, shape, rhythm, balance, color, tectonics, structure, etc.), elements (e.g., line, figures, objects, space, etc.) and organizational rules (e.g., hierarchy, layering, typology, symmetry, etc.) of formal design are used to create the representation model organizing physiologic data

The relevance of ***architectural research*** focused on the design, construction and communication of data representations is supported by the leading minds in the architectural field as a natural extension of designing and building functional forms and spaces (Anders 1999, Benedikt 1991, Mitchell 1995, Negroponte 1995). Until recently, most of the architectural work in the area had been restricted to cases involving simple and non-dynamic data sets with elementary functional and interface requirements. This is beginning to change as few and promising works show (Asymptote 1999, Chu 1998, Davis 1996,Möller 1996, Novak 1998, 1995). However, none of the ongoing data representation design activity addresses the type of theoretical and practical issues of this research proposal.

3 Application Area: Anesthesiology

Unexpected incidents are common in critical care medicine (Cook et al 1991, Cook and Woods 1994, Gaba 1994). Anesthesiologists face them during 20 percent of all anesthetics. One quarter of these incidents represent critical events posing significant danger to patients (Allnutt 1987, Forrest et al 1990, Emergency Care Research Institute (1985, Pierce 1985). Looking back at the patients who suffered injury over the past 13 years, 72% of the adverse outcomes could have been prevented if the patient had been better monitored (Webb 1993). “Critical incident studies”, which originated in the mid-1950s in military aviation safety research, were introduced into anesthesia by Cooper et al in 1978 and 1980. The studies recognize that adverse outcomes frequently are catastrophic endpoints of an “evolving” chain of often subtle incidents, which alone might not have progressed into disasters (Gaba 1987). Therefore, quick and accurate decisions are a major concern in anesthesia.

The research team confronted the visualization design problem of having to represent 32 interrelated, non-spatial physiologic variables in real time *and* in a way that improved detection, diagnosis and treatment accuracy and speed over the existing data representation system. Presently, anesthesiologists watch all 32 parameters plotted separately as 2D waveform charts and numbers to determine if a patient is stable and in the desired physiologic state (see Figure 1).

4 Methodology and Procedures

The research has been conducted by an interdisciplinary team consisting of experts and graduate students in Architecture, Bioengineering, Computer Science, Medicine, and Psychology. If, on one hand, the importance of multidisciplinary work cannot be understated —the nature and complexity of the visualization problem could have never been addressed by any one discipline alone—, on the other hand there are great logistic, methodological and ‘cultural’ challenges in making people from different fields and locations work together.

During the first 2 years, the team interactions naturally evolved toward the operational framework of the design process. We found that the design process was the most effective and efficient collaborative methodology to get the members of the group talking and working with one another. Despite the fact that the validity of this type of inquiry has been amply demonstrated (Cross 1986, 1882, Lawson 1980, Rittel 1986, Rowe 1987, Schön 1983) (and to the surprise of those in architecture) this was a real finding for our colleagues in other disciplines. After some initial doubt, they have now come to accept the design process as a systematic and experimental procedure for advancing, developing, testing, selecting and communicating hypotheses. Design inquiry is thus our team’s normal methodology for developing both basic and applied types of knowledge.

Each PI has primary responsibility in their field of expertise and is expected to communicate and collaborate with the rest of the team. Group meetings are held weekly (within a discipline) and monthly (of the whole group). Other meetings (e.g., between two disciplines) are often informally held through the interactions of graduate students and often overseen by at least one PI. All meetings are expected to include members from the other disciplines (often graduate students if PI may not attend). A protected web site with state-of-the-art features allowing collaboration is used to keep everyone updated of ongoing developments and allow feedback. The site also serves to maintain a record of the decision making and design process. External consultants have been often invited to evaluate and/or participate at various phases of the process. Web technology has enabled us to make most use of our out-of-town consultants input. A public accessible web site may be found at: http://infoviz.chpc.utah.edu/anes1.htm. Figure 2 shows a diagram of the overall design process circle we use in conducting our research.

More specifically, creating the visualization model involved the following steps:

- analyzing known physiologic phenomena to be monitored, including desirable (i.e., normal) and undesirable states;
- analyzing the anesthesiologist's decision making process, including acquired behaviors and group influence;
- analyzing all available variables and relations or functional dependencies among them, and prioritizing their inclusion into the application;
- developing a conceptual model representing the critical functions to be monitored, including the relationships among their variables (user's mental model);
- analyzing and defining essential semiotics of 2D and 3D design based on existing research on human factors, cognitive psychology and architectural and design theory;
- formulating a visual design whereby 3D objects, attributes, spaces and frameworks follow the conceptual model;
- designing software, with principles of modularity and distribution over networks;
- testing the design and software with users;
- iterate the process, as described in Figure 2.

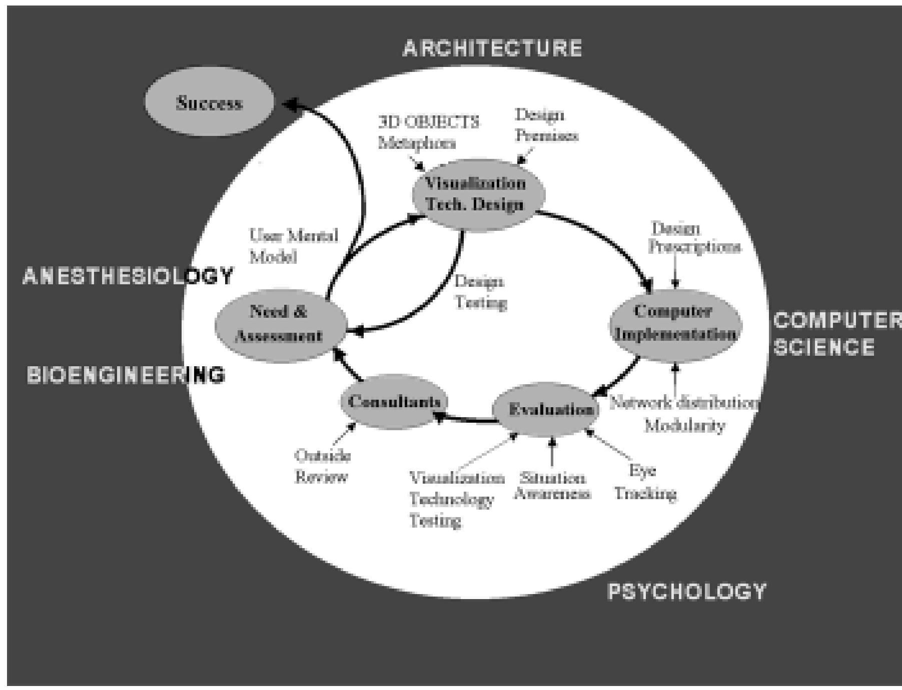

Figure 2. Team Operation Methodology. Design Process as Inquiry

During the initial part of the project, design ideas were developed and modeled using the non-real time programming environment of SGI Explorer or IBM Data Explorer. Still images of these visualization models were used to conduct direct interviews with anesthesiologists. Several iterations of these meetings took place until we arrived to a model in which clinicians could recognize variables and functions quickly and easily. At that point, we moved to encode the model's design prescriptions into a software running on both Unix and Windows operating systems. The software was also written to allow real time transmissions over networks with moderate bandwidth. During software development and testing we used the body simulator METI to generate the necessary physiologic data related to diverse clinical scenarios (see Figure 4 and "Evaluation" section below). Further evolution of the visualization software version took place in the past year based on continuous interactions with anesthesiologists and bio-engineering and medicine graduate students. The visualization model presented in this paper is the last version of this iteration (see Figure 3 below).

5 Premises

The research team agreed to apply the following seven design premises to guide its data visualization design process (the first three already introduced earlier):

- *inventing a formal semiotics* to link graphics and physiologic meaning;
- *integrating data* so that representations reveal data's relationships and interactions;

- *providing interactivity* to facilitate user's access to the information;
- mapping information into a *3D data representation architecture* in order to improve recognition while supporting data integration and significant increases in the number of variables to be displayed;
- *using an ordinary PC platform* to insure universal adaptability and adoption in medical settings;
- *allowing network distribution* to support data visualization as well as raw data access at any distance (at moderate bandwidth);
- aiming at formal, functional, and technical *simplicity*.

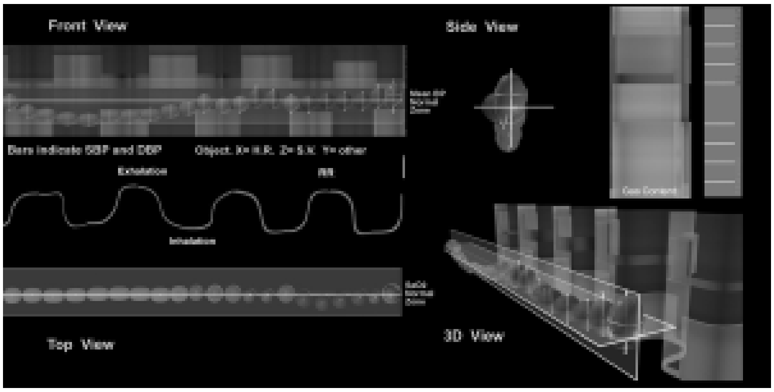

Figure 3. New visualization system for displaying physiologic data in real time.

Simplicity has been the key design premise that helped us to respond to all the rest of premises. It was evident from the outset and later proven correct that data integration, 3-D graphics, interactivity, successful graphic semiotics, real time computer processing on a PC platform as well as network distribution would only work if we kept a high level of design simplicity. This has been achieved by working with geometric primitives and abstractions related to fundamental laws of human perception. We used the following simple yet powerful design principles to encode perceptual clues:

(1) Choice of geometry
(2) Geometric deformation
(3) Overlapping/separation/intersection
(4) Figure-ground/layers
(5) Movement/Trajectory (up-down, front-back) (focus)
(6) Size and Location
(7) Scale and Proportion
(8) Attributes (color, texture, opacity, etc.)
(9) Spatial relationship between elements
(10) Composition and pattern recognition
(11) Interactive viewpoints of same data
(12) Reference frames

The project being presented in this paper shows the visualization modeling of 13 physiologic variables. The reason for reducing the number of parameters from 32 to 13 was based on the lack of enough resources at the start of this research project. This reduction made the task manageable while still presenting visualization design and computing challenges that were qualitatively identical (and thus any design solution transferable to) a fully-fledged 32 variable data representation architecture. In addition, having 13 parameters also allowed the testing and implementation of the seven design premises the team had established. For example, 13 variables changing in real time creates a multiple dimension representation problem that favors 3D over 2D graphics, as 3D visualizations tend to better express the range of variabilities and subtleties of multi-variable defined physiologic states.

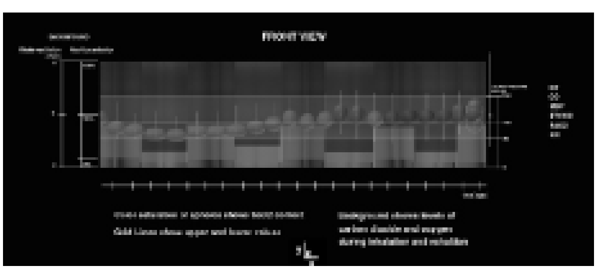

Figure 4. Front view of the visualization system

The choice of which 13 variables to depict was based on two reasons. First, the heart and the lungs are the two *"critical functions"* that require most medical monitoring and management during anesthesia. Second, cardiac activity and respiration are naturally interdependent, thus facilitating data integration design considerations. The 13 physiologic variables modeled correspond to:

- *Cardiac Function* (updated each heart beat) includes Stroke Volume, Cardiac Output, Heart Rate, Blood Pressures, and Arterial Oxygen Saturation.
- *Respiratory Function* (updated each breath) includes Tidal Volumes, Respiratory Rate, Nitrous Oxide, Oxygen, Carbon Dioxide, and Airway Pressure.

6 Result

Figure 3 shows our 3-D visualization system for displaying physiologic data in real time. The same data is displayed in four interactive windows; each one designed to show certain information in detail and complementarily. Departure from "normal" reference grids, shapes, spacing, and colors helps the clinician ***discover change***. The display structure maps each variable to a clinician's mental model, to help ***diagnose problems***. Functional relationships link the elements of the display to help the clinicians ***treat problems***.

Data modeling follows specified configurations in X-Y-Z coordinates, in real time. A 3D data architecture first organizes the 13 measured variables into data sets or "critical functions" that are then mapped to 3D objects. These objects work as metaphors of cardiac and respiratory functions. The foreground red spheres represent cardiac activity. The background plane communicates respiratory activities. The objects' location and movement in space as well as their attributes (e.g., shape, texture, opacity, color, etc.) map further data. Specially designed lines and points establish referential datum to detect abnormality. Time moves from right to left (in X), with present conditions at the "front" or right edge of each view. Past states remain to permit a 'historical view' of the data.

More specifically, the "cardiac" object grows and shrinks with each heartbeat as data is updated. Its height is proportional to the heart's Stroke Volume and its width is proportional to Heart Rate. Its total volume is proportional to the heart's total Cardiac Output. The position of this spherical object in Y and Z space is proportional to the patient's (a) Mean Blood Pressure (moving up is higher, moving down is lower) and (b) the Oxygen Saturation in the blood (moving backward is lower, moving forward is higher) respectively. The object's color indicates the patient's overall oxygenation level. The graphic icon offers an useful similarity to a working heart, thus facilitating intuitive and quick recognition. A perfectly round object reflects normalcy whereas an oblong or squash one reflects abnormalcy. If the object is centered on the horizontal and vertical grid frame, the patient is normal. If it is above or below the reference line, the patient's blood pressure is abnormal. The front view shows a trend plot where the Blood Pressure fell and then returned to normal (Figures 3 and 4). In addition, the same view shows that the drop in the Blood Pressure was due to an inadequate Stroke Volume and decreased Heart Rate.

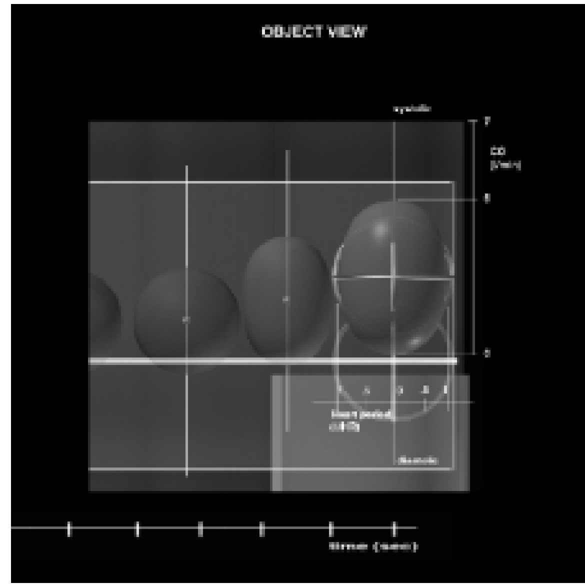

Figure 5. Detail of the Front View depicting present conditions.

Critical respiratory function data are mapped to a bluish 'curtain' plane in the background. This object's undulation back and forth in Z space plots Inhalation, Exhalation and Respiratory Rate information (Top View in Figure 3). Data relative to gas types and volumes are mapped in Y space. Variance of gray and green colors shows inspired and expired gases and their concentrations (Oxygen and Carbon Dioxide). Quantitative measurements of Gas Concentrations and Airway Pressure are best seen in the side view (Figure 6). The height of the "curtain" is proportional to Respiratory Tidal Volume.

A series of frameworks establishing normal values are offered to help detect departure from normalcy. The spherical grid frame that continuously appears with the 'cardiac' object in the present moment shows the expected normal values for Stroke Volume, Heart Rate and Cardiac Output. The horizontal reference lines correspond to a patient's normal values of Mean Blood Pressure (Front View) and Oxygen Saturation (Top View). Figure 5 shows a zoomed-in Front View of the present physiologic conditions. The spherical grid frame partially hidden by the cardiac object shows a normal Heart Rate and a slightly larger than ideal Stroke Volume. The position of the cardiac object within the band of normal Mean Blood Pressure assures normalcy. The display also permits to set the normalized reference grids so that they match a patient's normal condition. Similarly, referential planes are utilized to define normal respiratory rate and gas volumes for the "respiratory" object.

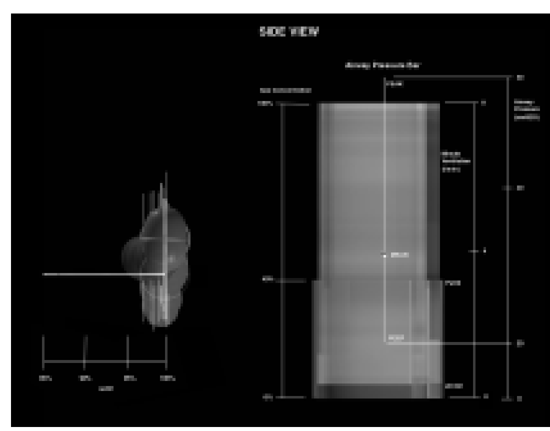

Figure 6. Side View of the visualization system

The data were purposely mapped into the objects and spaces so that the Front, Side and Top Views (or windows) presented users with specific physiologic information. For example, the Front View focuses on continuous and discrete depictions of a particular relationship among particular variables, i.e., the interactions among Blood Pressure, Heart Rate, Stroke Volume in relation to Gas Concentrations (O2, CO2, etc.).

Of the four views, the Side View (Figure 6 below) is critical in establishing the present physiologic state of the patient. It has been designed to work and look like a physiologic 'target' for the anesthesiologist to aim at. Attention is continuously drawn to this view. Only when conditions depart from

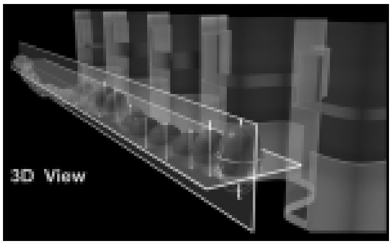

Figure 7. Interactive window displaying a 3D expression of the data. Note referential frame

normalcy, the clinician moves to the other views to detect and establish some pattern and trend in the data. Top and Front Views show the "life space" or physiologic history of the patient. These two views allow for analysis and comparison. The 3-D View provides a uniquely comprehensive, integrated and interactive view of all physiological data at once (Figure 7 below).

The combination of all 4 windows provides the anesthesiologist a hitherto unavailable depiction of the working relationship among 13 discreet variables in human physiology. Although this window system is very familiar to architects and designers in general given its reference to architectural views and CAD software, it constitutes a completely new way of looking at data for people in Medicine, Bioengineering, Computer Science and Psychology. This is a good example of how something quite ordinary and obvious in one discipline gets successfully exported to and praised as novel and useful by other disciplines.

7 Evaluation of the Visualization Model

Our research hypothesis had been that a 3D data representation architecture conveys the health status of a patient at a glance, thereby reducing the cognitive workload and speeding up the detection of problems when they occur. We tested this claim by comparing the traditional display and our visualization prototype (Figures 1 and 3 respectively). We used the body simulator METI to generate the necessary physiologic scenarios for the test (Figure 8). METI consists of a mannequin placed on an operating room table that simulates human physiologic functions and responses to anesthesia. METI generates all the physiologic data necessary to run both the traditional and new visualization display in real time.

METI was preprogrammed with 3 critical events in isolation and "situation awareness" tests conducted on two groups, one using the traditional display and the other one with ours. Subjects included bioengineering graduate students. The results show gains in recognition times that are statistically significant. See Table 1 below.

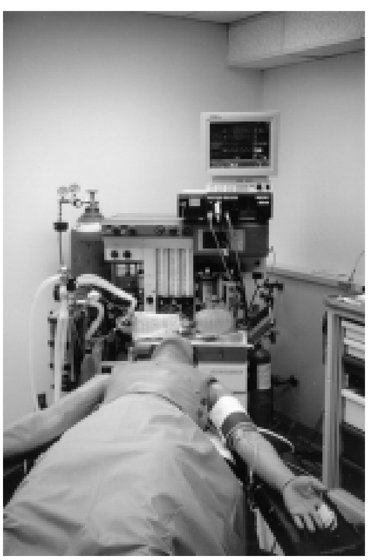

Figure 8. The METI body simulator

Another important finding was that experts were overtaken by being able to witness physiologic interactions between cardiac and respiratory activities that, although well known, have never been "seen" before. In fact, several new insights have been attained when analyzing their interactions during abnormal physiologic states. These insights have avoided anesthesiologists simply because of the way data has been presented to them until now. This points to a real advantage of visualization models that integrate variables: not only do they support ordinary decision making but also permit new ways of looking at the data that may lead to new detection, diagnosing and treatment methods.

After-test interviews, direct observations of how users interact with the new system vis-a-vis the traditional display, and informal conversations with anesthesiologists suggest that the visualization system developed tends to work very successfully at the qualitative level, as it provides a comprehensive understanding of physiologic states. However, it is less successful when detailed and quantitative types of information are necessary. It appears that our visualization model works best for rapidly detecting and diagnosing problems but that needs improvements when dealing with treatment and certain diagnosis as more detailed and quantitative information is often necessary. This perhaps suggests the necessity to incorporate some key quantitative indicators into our visualization model.

During informal testing and presentations, we also found that the integrated 3D data visualization design allows reasonable levels of operability even in people with little or no knowledge in human physiology. This may prove very important for applying the visualization method to medical areas in which lower levels of expertise may be available (e.g., nurse stations in critical care units and hospital bed monitoring, casualty care in theaters of war). Further work in this direction is clearly needed.

8 Conclusion

The interdisciplinary collaboration among Architecture, Bioengineering, Computer Science, Medicine and Psychology have produced novel methodologies and models to access, organize, represent, and interact with non-spatial databases in real time. Preliminary test results of our work, the development of a patent-pending visualization technology, and the legitimization of our premises and methodology by a recently received $2.2M NIH grant to support five more years of visualization research acknowledge the concrete contribution made by Architecture to the monitoring of physiologic states in Anesthesiology.

Based on this positive feedback, the research team is now working to enhance and extend the capabilities of the developed visualization system. Within the next 2 year we plan to pursue the following goals:

CRITICAL EVENTS	HYPOVOLEMIA		ISCHEMIA		BRONCHOSPASM	
	TRADITIONAL	CROMDI	TRADITIONAL	CROMDI	TRADITIONAL	CROMDI
Detection (# of correct answers)	1.8	2.4	1.8	2.2	2.8	2.8
Diagnosis (# of correct answers)	1.4	2.2	2.8	2.2	2.8	3.4
Recognition Time (seconds)	96	48	138	126	180	120

Table 1. Testing of visualization system for Anesthesiology Comparison testing between Traditional and the new Visualization System (CROMDI) was done using 12 Bioengineering graduate students. Situation awareness questions were asked every 2.5 minutes and recognition time was measured when critical changes were seen. (Zhang et al 2000)

- include the remaining 19 physiologic variables to allow the full monitoring of physiologic states during anesthesia;
- incorporate quantitative data representations to accommodate the need for specific numerical information;
- supplement our visualization design with sounds to significantly enhance the display of information;
- develop the software interface to allow more customization of visualization parameters, number and type of windows displayed, normal value definition, and data visualization formats.

Several tests with experts are scheduled for the next two years. The incorporation of a recently acquired eye-tracking device for some of these tests, the use of larger populations and more refined testing protocols will surely produce results that will improve our understanding of the mechanism behind data visualization. These results will in turn lead to improvement in the design and computation aspects of the visualization model.

We are hopeful that by addressing the largely forgotten visualization needs of physiologic monitoring in Medicine, we will be produce important improvements in the understanding of and response to critical medical conditions. Designing, building, and computing 3D data architectures may thus prove to not only serve the social welfare of people but also respond to functional, technological and indeed aesthetic needs not unlike those addressed by traditional physical architecture. Hence, we would like to conclude proposing that the architectural discipline must expand its too often narrowly defined area of expertise to acknowledge and include the exciting new areas of architectural practice opened up by the digital revolution.

Acknowledgements

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