A Mixed Reality Approach for Interactively Blending Dynamic Models with Corresponding Physical Phenomena

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The design, visualization, manipulation, and implementation of models for computer simulation are key parts of the discipline. Models are constructed as a means to understand physical phenomena as state changes occur over time. One issue that arises is the need to correlate models and their components with the phenomena being modeled. For example, a part of an automotive engine needs to be placed into cognitive context with the diagrammatic icon that represents that part's function. A typical solution to this problem is to display a dynamic model of the engine in one window and the engine's CAD model in another. Users are expected to, on their own, mentally blend the dynamic model and the physical phenomenon into the same context. However, this contextualization is not trivial in many applications.

Our approach expands upon this form of user interaction by specifying two ways in which dynamic models and the corresponding physical phenomena may be viewed, and experimented with, within the same human interaction space. We present a methodology and implementation of contextualization for diagram-based dynamic models using an anesthesia machine, and then follow up with a human study of its effects on spatial cognition.

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1. INTRODUCTION

A simulation modeler must consider how a model (e.g., dynamic) is related to its corresponding physical phenomenon. Understanding this relationship is integral to the simulation model creation process. For example, to create a simulation based on a functional block model of a real machine, the modeler must know which machine parts each functional block represents; the modeler must understand the *mapping* from the real phenomenon to each functional block. That is, the modeler performs a mental geometric transformation between the components of the model and the components of the real phenomenon. The ability to effectively perform this transformation is likely dependent on spatial ability (e.g., the ability to mentally rotate objects), which is highly variable in the general population. Modelers or learners with low spatial ability may have difficulty mentally mapping a model to its real phenomenon. The purpose of this research is to: (1) engineer a mixed reality-based method for visualizing the mapping between a dynamic simulation model and the corresponding physical phenomenon, and (2) perform human studies to analyze the cognitive benefits of our method for mapping.

Understanding and creating these mappings represents a challenging task, since for diagram-based dynamic models, complex physical and spatial relationships are often simplified or abstracted away. Through this abstraction, the mapping from the model to the corresponding physical phenomenon often becomes more ambiguous for the user. For example, consider a Web-enabled, diagram-based, dynamic, transparent reality [Lampotang 2006] model of an anesthesia machine (Figure 1), called the Virtual Anesthesia Machine (VAM) that is implemented in Director (Adobe) and used via standard browsers [Lampotang et al. 1999]. The VAM is similar to models that can be created in common modeling packages such as ARENA [Kelton et al. 2003] and Simulink [Dabney and Harman 1997].

Transparent reality, as used in the VAM, provides anesthesia machine users an interactive and dynamically accurate visualization of internal structure and processes for appreciating how a generic, bellows ventilator anesthesia machine operates. To facilitate understanding of internal structure and processes through visualization: (a) the pneumatic layout is streamlined and its superficial details are removed or abstracted, (b) pneumatic tubing is rendered transparent, (c) naturally invisible gases like oxygen and nitrous oxide are made visible through color-coded icons representing gas molecules (color-coding according to 6 user-selectable, widely-adopted medical gas color code conventions), and (d) the variable flow rate and composition of gas at a given location are denoted by the speed of movement and the relative proportion of gas molecule icons of a given color, respectively. Compared to a photorealistic

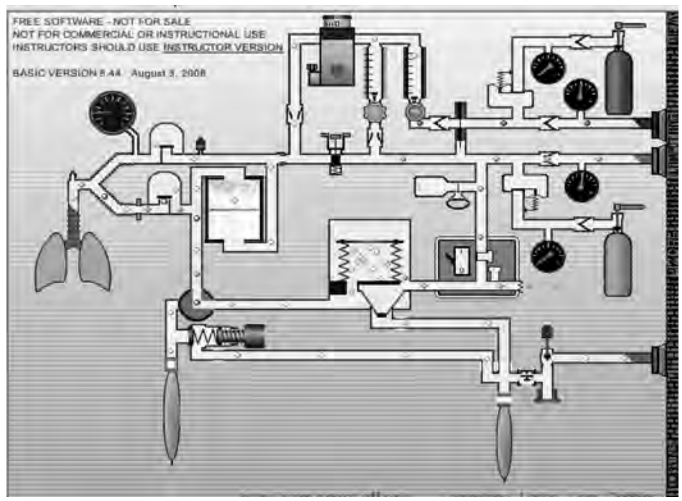

Fig. 1. The shockwave-based VAM, a diagram-based, Web-enabled, transparent reality, dynamic model of a generic anesthesia machine.

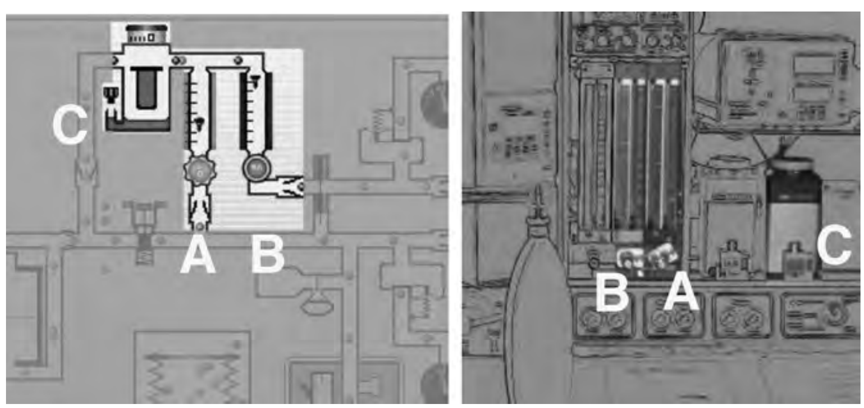

Fig. 2. The VAM (left) and the real machine (right). A is O_2, B is N_2O, and C is the vaporizer.

simulation that uses a simulation engine identical to VAM, the VAM has been shown to enhance understanding of anesthesia machine function [Fischler et al. 2008]. Students are expected to learn anesthesia machine concepts with the VAM, and apply those concepts when using the real machine.

To apply the concepts from the VAM when using a real machine, students must identify the mapping between the components of the VAM (the dynamic model) and the components of the real anesthesia machine (the physical phenomenon). For example, as shown in Figure 2, the O_2 knob (A) controls the amount of oxygen flowing through the system while the N_2O knob (B) controls the amount of nitrous oxide (N_2O), an anesthetic gas. These gases flow from the gas flowmeters and into B, the vaporizer. Note how the spatial relationship between the flowmeters (A and B) and the vaporizer (C) is laid out differently in the VAM than in the real machine.

That is, the flowmeters have been spatially reversed. In the VAM the N_2O flowmeter is on the right and the O_2 is on the left. Conversely, for the anesthesia machine, the N_2O flowmeter is on the left and the O_2 flowmeter is on the right. In all anesthesia machines the functional relationship between the flowmeters is the same, but the physical meters and knobs may be laid out differently in different machines due to engineering and ergonomic constraints. The purpose of the spatial reversal in the VAM is to make the gas flow dynamics easier to visualize and understand. Because the VAM simplifies these spatial relationships, understanding the functional relationships of the components is also easier (i.e., understanding that mixed O_2 and N_2O gases flow from the gas flowmeters to the vaporizer).

However, Dr. Samsun Lampotang, an anesthesia educator at the University of Florida, has noticed that this simplification can create difficulties for students when spatially mapping the VAM model to the anesthesia machine. This type of mapping problem has also been identified in psychology literature [Goldstone and Son 2005]. For example, students training with the VAM to use a real machine could memorize that to turn the left knob will increase the O_2. Then, when the students interact with the real machine, they will accidentally increase the N_2O instead. This action could lead to negative training transfer, which could ultimately lead to harming patients. Although understanding the mapping between the VAM and the anesthesia machine is critical to the anesthesia training process, mentally identifying the mapping is not always obvious. This mapping problem may be connected to spatial ability, which can be highly variable over a large user base. This research proposes that a mixed reality simulation could offer a visualization of the mapping to help the user visualize the relationships between the diagram-based dynamic model (e.g., the VAM) and the corresponding real phenomenon (e.g., the real anesthesia machine).

We present a method of integrating a diagram-based dynamic model, the physical phenomenon being simulated, and the visualizations of the mapping between the two *into the same context*. To demonstrate this integration, we present the Augmented Anesthesia Machine (AAM), a mixed reality-based system that combines the VAM model with the real anesthesia machine (Figure 3). First, the AAM spatially reorganizes the VAM components to align with the real machine. Then, it superimposes the spatially reorganized components into the user's view of the real machine (Figure 1). Finally, the AAM synchronizes the simulation with the real machine, allowing the user to interact with the diagram-based dynamic model (VAM model) through interacting with the real machine controls such as the flowmeter knobs. By combining the interaction and visualization of the VAM and the real machine, the AAM helps students to visualize the mapping between the VAM model and the real machine.

We summarize prior work [Quarles et al. 2008a, 2008b, 2008c] in contextualization and extend it in this article by contributing the following: (1) extensive implementation details of iterative design processes, (2) additional visualizations (i.e., a heads-up display and a visual transformation between the model and the physical phenomenon), and (3) new human subject analyses to

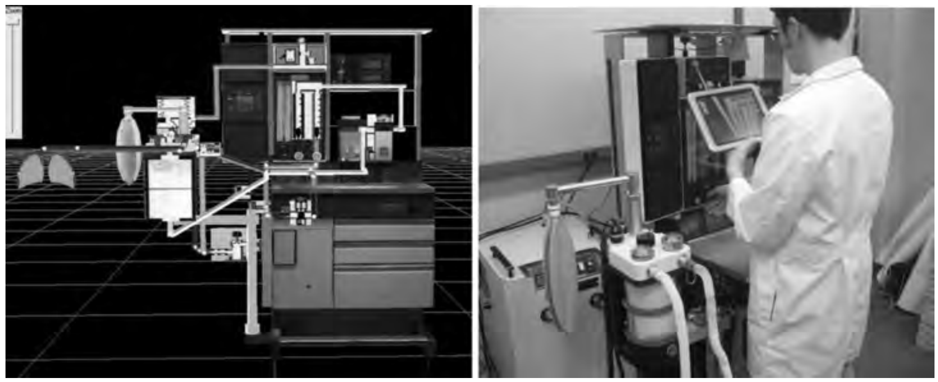

Fig. 3. (Left): The diagrammatic VAM icons are superimposed over a model of an anesthesia machine. (Right): A student uses the magic lens to visualize the VAM superimposed over the real machine.

evaluate the effectiveness of our contextualization approach and its impact on user spatial cognition.

2. RELATED WORK

Computer modeling and simulation has been a vibrant area of research and practice since the development of the analog computer and the use of models for operations research [Tocher 2008; Nance 1971; Nance and Sargent 2002; Wilson and Goldsman 2001]. This section overviews the research that led us to the integration of simulation and modeling, human-computer interfaces, and mixed reality (for an expanded description of related work, see Section 1 of the online appendix that can be accessed in the ACM Digital Library).

2.1 Modeling and Simulation (M&S)

Models are represented in program code (for numerous examples, see Law and Kelton [2000]) or mathematical equations [Banks et al. 2001], but many of these models can also have visual representations. For example, GASP IV incorporated model diagrams [Pritsker 1971]. A good repository of visual model types can be found in Fishwick [1995].

This shift to visual modeling made modeling tools more accessible and usable for modelers across the field of simulation. For example, Dymola [Otter 1996] and Modelica [Mattsson 1998] evolved from analog computation [Cellier 1991] and are languages that support real-time modeling and simulation of electromechanical systems using visual modeling tools.

Pidd [1996] outlines major principles that can aid in designing a discrete-event modeling editor with high usability and acceptance by users. These principles are derived from more general HCI principles presented in Norman [1988], and supported by theories about learning and cognitive psychology [Kay 1990].

2.2 Virtual Reality and Simulation

Virtual Reality (VR) is a related field that addresses many HCI issues. For example, VR has been utilized to address ergonomics challenges [Whitman et al. 2004]. Many VR applications in modeling and simulation are outlined in Barnes [1996]. Macredie et al. [1996] identify the inefficiencies of typical VR systems when integrating simulation, and propose a unifying communication framework for linking simulation and VR. Grant and Lai [1998] expand on this by using VR as a 3D authoring tool for simulation models. There is a wealth of research that has been conducted on VR-based simulation [Brooks 1999; Macedonia 2002; Burdea and Coiffet 2003], especially in medical simulation [Seymour et al. 2002; Gallagher 2005; Verdaasdonk 2006].

2.3 Integrative Modeling

The concept of integrative modeling was introduced by Fishwick [2004]. The goal of this sort of modeling is to treat modeling as part formal diagrammatic specification, and part human-computer interface. Previous work focuses on: (1) creating an ontology framework that is used to capture the underlying semantics required for building the human interface [Shim 2006, 2007], and (2) illustrating the use of this framework through military communications network and ecosystem examples [Park 2004, 2005]. Park and Fishwick [2005] showed that it was possible not only to use the ontology to bridge models, but also to automatically construct the human-interface event code from the ontology.

The work presented in this article relies on the concepts laid out by the previous efforts in integrative modeling. We present an integrative method, using mixed reality to combine an abstract simulation with the physical phenomenon.

2.4 Mixed Reality

In 1994, Milgram and Kishino [1994] laid the framework for new area of virtual reality research called Mixed Reality (MR) that takes a different approach to interaction and visualization. Instead of simulating a purely virtual world, MR systems visually and interactively combine the virtual world with the real world. Milgram presents the Virtuality Continuum, a taxonomy of the different categories in which MR can "mix" virtual and real objects in a mixed environment in which real and virtual objects are seamlessly integrated into one visual and interactive space.

The AAM uses a magic lens as its primary display device for mixed environments. Magic lenses are hand-held tangible user interfaces [Ishii and Ullmer 1997] and display devices as in Looser [2004]. With a magic lens, the user can look through a lens and see the real world augmented with virtual information within the lens's "region of interest" (i.e., LCD screen of a tablet-based lens) from the user's first-person perspective.

3. SPATIAL COGNITION

Spatial cognition addresses how humans encode spatial information (i.e., about the position, orientation, and movement of objects in the environment), and

Fig. 4. A magnified view of the gas flowmeters on the real machine.

how this information is represented in memory and manipulated internally [Hegarty et al. 2006]. We considered spatial cognition of end users when we were designing the AAM to address the spatial mapping problem between the VAM and the real machine (for information on specific spatial ability tests, see Section 2 of the online supplement).

4. THE VAM AND THE ANESTHESIA MACHINE

The purpose of the present research is to offer methods of combining real phenomena with a corresponding dynamic, transparent reality model. Before detailing the methods and implementation of contextualization, this section describes how students interact with the real machine and the model (the VAM) in the current training process. The following example shows how students interact with one anesthesia machine component (the gas flowmeters) and describes how students are expected to mentally map the VAM gas flowmeters to the real gas flowmeters.

4.1 The Gas Flowmeters in the Real Anesthesia Machine

A real anesthesia machine anesthetizes patients by administering anesthetic gases into the patient's lungs. The anesthesiologist monitors and adjusts the flow of these gases to make sure that the patient stays safe and under anesthesia. The anesthesiologist does this by manually adjusting the gas flow knobs and monitoring the gas flowmeters as shown in Figure 4. The two knobs at the bottom of the right picture control the flow of gases in the anesthesia machine and the bobbins (floats) in the flowmeters above them move along a graduated scale to display current flow rate. If a user turns the color-coded knobs, the gas flow changes and the bobbins move to indicate the new flow rate.

4.2 The Gas Flowmeters in the VAM

The VAM models these gas flow control knobs and bobbins with 2D icons (Figure 5) that resemble the gas flow knobs and bobbins on the real machine. As with the real machine, the user can adjust the gas flow in the VAM by turning the knob icons in the appropriate direction (clockwise to decrease and counterclockwise to increase) with a mouse. Since the VAM is a 2D online simulation, the user clicks and drags with the mouse in order to adjust the knob icons.

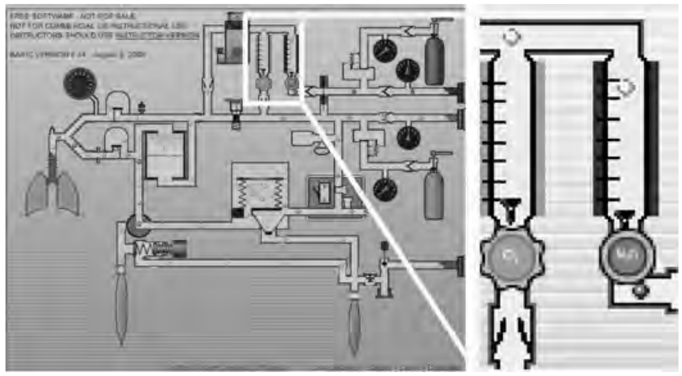

Fig. 5. A magnified view of the gas flow knobs and bobbins in the VAM.

When the user turns a knob, the rate of gas flow changes in the visualization; animated color-coded gas particles (e.g., blue particles = N_2O; green particles = O_2) change their speed of movement accordingly to represent the magnitude of the flow rate. These gas particles and the connections between the various machine components are invisible in the real machine. As a transparent reality simulation, the VAM models the invisible gas flow, internal connections, interaction, and the appearance of the real gas flowmeters. Within this modeling, there is a mapping between the real machine's gas flowmeters and the VAM's.

5. CONTEXTUALIZATION DESIGN METHODOLOGY

One way of visualizing this mapping is to "contextualize" the model with the real phenomenon. Contextualization involves two criteria: (1) *Registration*: spatially superimpose parts of the simulation model over the corresponding parts of the real phenomenon (or vice versa) and (2) *Synchronization*: temporally synchronize the simulation with the real phenomenon.

Originally proposed in Quarles et al. [2008a], two methods are described through the example of mapping the VAM simulation to the anesthesia machine. The purpose of these two specific methods is to help students orient themselves to the real machine after learning with the VAM. These methods have also been extended with additional visualizations described in Sections 5.1.3 and 5.3. The students may start with the VAM, and proceed through one or both of the following contextualization methods before learning with the anesthesia machine.

5.1 Contextualization Method 1: Real Machine-Context

One way to visualize the mapping between a diagram-based dynamic model and real phenomenon is to spatially reorganize the model layout and superimpose the model's components over the corresponding components of the real phenomenon. Using this method, the components of the VAM (e.g., gas flowmeters icon, vaporizer icon, ventilator icon) are spatially reorganized and superimposed onto the context of the real machine (Figure 6). Each model component is repositioned in 3D to align with the corresponding real component. Through

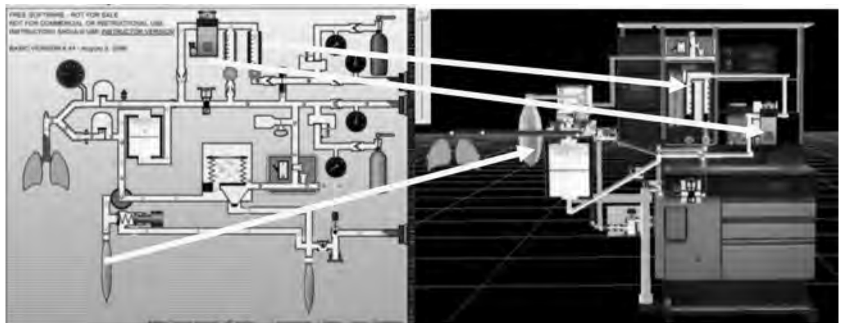

Fig. 6. The VAM (left) is spatially reorganized to align with the real machine (right).

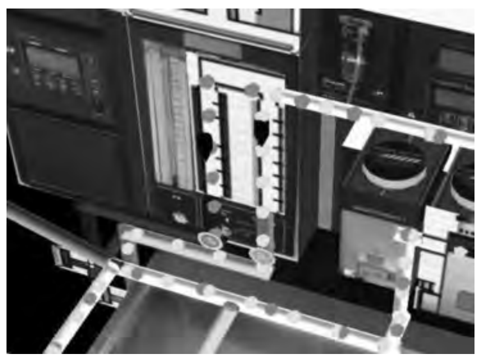

Fig. 7. The user's view of the flowmeters in the AAM.

this alignment, the user is able to visualize the mapping between the VAM and the real machine.

For example, consider contextualizing the VAM's gas flowmeters with the real anesthesia machine's gas flowmeters (Figure 7). The flowmeters are superimposed over the user's view of the real flowmeters. This visualizes the mapping between the real machine and the simulation model. In the AAM, the gas particle visualization still flows between the same components with the same underlying model, but the flow visualization takes a 3D path through the real machine.

5.1.1 *Visualization with the Magic Lens.* With a tracked 6DOF magic lens (Figure 8), users can view a first-person perspective of the VAM model in context with a photorealistic 3D model of the real machine. The 3D machine model appears on the lens in the same position and orientation as the real machine, as if the lens was a transparent window (or a magnifying glass) and the user was looking through it. The relationship between the user's head and the lens is analogous to the OpenGL camera metaphor. The camera is positioned at the user's eye, and the projection plane is the lens; the lens renders the VAM simulation directly over the machine from the perspective of the user.

Fig. 8. The real view and the magic lens view of the machine shown from the same viewpoint.

Fig. 9. A user turns the N_2O knob on the real machine and visualizes how this interaction affects the overlaid VAM model.

5.1.2 *Interaction.* The simulation is synchronized to the real machine controls, which enables users to interact with the simulation through their interactions with the real machine For example, if a user turns the N_2O knob on the real machine to increase the real N_2O flow rate (Figure 9), the simulated N_2O flow rate will increase as well. Then the user can visualize the rate change on the magic lens interactively, as the blue particles (icons representing the N_2O gas "molecules") will visually increase in speed until the user stops turning the knob. With this synchronization, users can observe how their interactions with the real machine affect the model in context with the real machine.

5.1.3 *HUD Visualization.* To prevent disorientation when transitioning from the VAM to the AAM, a Heads-Up Display (HUD) was implemented (Figure 10). The HUD shows the familiar VAM icons which are screen aligned and displayed along the bottom of the lens screen; each icon has a 3D arrow associated with it that always points at the corresponding component in the anesthesia machine. Thus, if the user needs to find a specific VAM component's new location in the context of the anesthesia machine, the user can follow the arrow above the HUD icon and easily locate the spatially reorganized VAM component. Once the user has located all the reorganized VAM components, the user can optionally press a GUI button to hide the HUD.

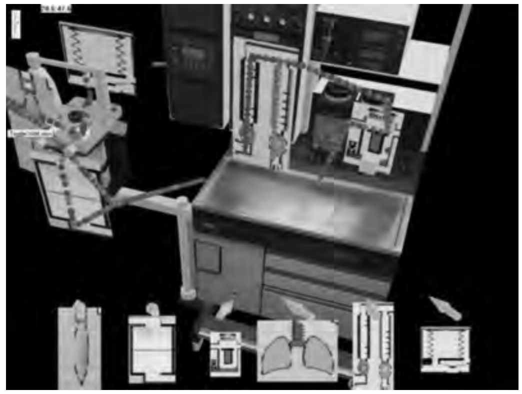

Fig. 10. The menu at the bottom of the HUD points the user in the direction of each spatially reorganized VAM component in 3D. The tubes have been removed to make the icons more visible.

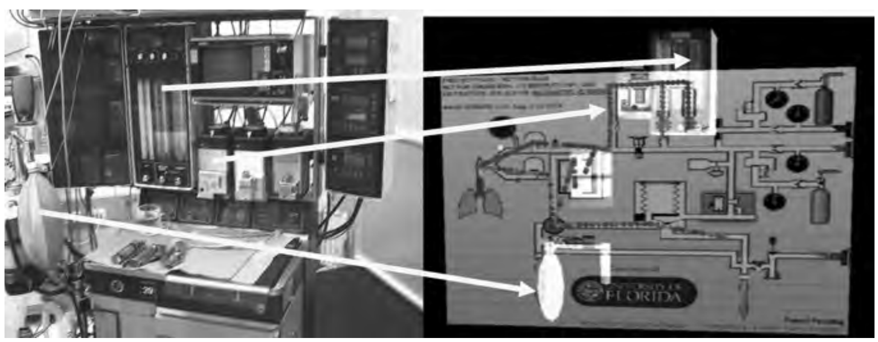

Fig. 11. The real machine (left) is spatially reorganized to align with the VAM (right).

5.2 Contextualization Method 2: VAM-Context

Another way to visualize the mapping between a real phenomenon and its model is to spatially reorganize the real phenomenon itself so that its components are superimposed into the context of the dynamic model (Figure 11). This method takes a 3D anesthesia machine model and reorganizes it on the 2D plane of the VAM. Instead of looking through the magic lens like a transparent window, the tablet PC lens is just a hand-held screen that displays a 2D simulation from a stationary viewpoint. Essentially, this mode enables the user to control the 2D VAM visualization through interaction with the real anesthesia machine (see Section 3.1 of the online supplement for more details and a picture of interaction).

5.3 Transformation between VAM-Context and Real Machine-Context

Users might prefer to interactively transition between two methods depending on individual learning needs. To create a smooth transition between VAM-context and real machine-context, a geometric transformation was implemented. The 3D models (the machine, the 3D VAM icons) animate smoothly between the differing spatial organizations of each contextualization method (for

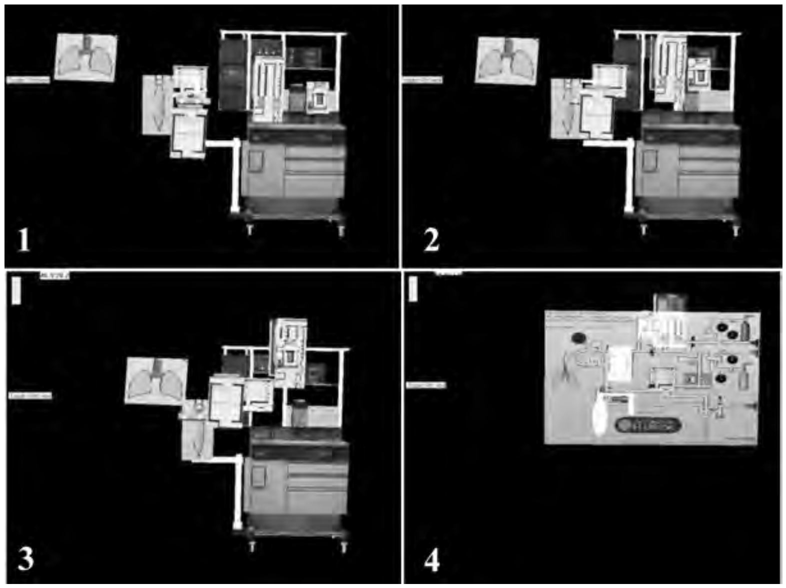

Fig. 12. Geometric transformation between the AAM and the VAM.

a step-by-step description of this transition, see Section 3.2 of the online supplement). This transformation "morphs" from one contextualization method to the other with an animation of a simple geometric transformation (Figure 12).

To facilitate this transformation between the two methods, we implemented a semantic network that represents the mapping between each 3D model of a real machine component (i.e., the gas flowmeters) and each corresponding VAM icon. When the user changes the visualization method, the components and the particles all translate in an animation to the positions contained in their semantic links. These transformation animations help to demonstrate the mappings between the real machine and the VAM model, thereby offering students a better understanding of the linkage between the VAM model and the AAM.

6. IMPLEMENTING CONTEXTUALIZATION

This section will explain the engineering challenges of: (1) visual contextualization (i.e., displaying the model component in context with the real component), (2) interaction contextualization (e.g., interaction with the real phenomenon affects the state of the model), and (3) integrating the tracking and display technologies that enable contextualization (Figure 13). The engineering approach presented in this section is conceptually built around the educational goal of helping students to transfer and apply their VAM knowledge to the real anesthesia machine.

6.1 Visual Contextualization

The main engineering challenge here is how to display two different representations of the same object (e.g., the 3D anesthesia machine and the 2D VAM)

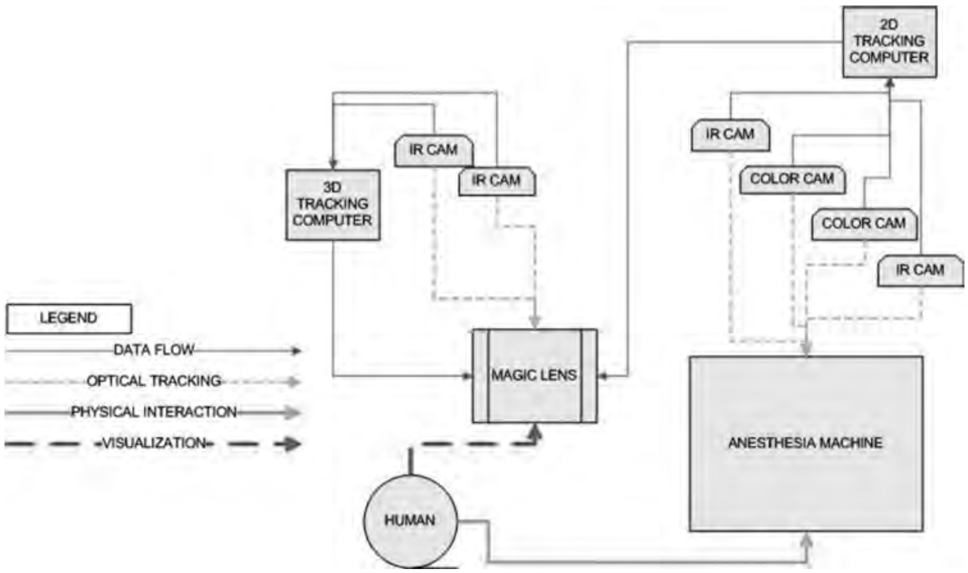

Fig. 13. Schematic diagram of the AAM hardware implementation.

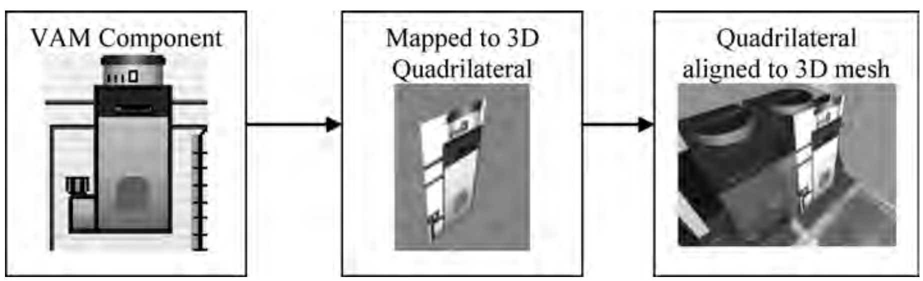

Fig. 14. Transforming a 2D VAM component to contextualized 3D.

in the same space. Our approach to visual contextualization addresses this challenge.

6.1.1 *Geometric Transformations from 2D to 3D.* Each VAM component is manually texture-mapped to a quadrilateral (i.e., a 3D polygon defined by four vertices) and then the quadrilateral is scaled to the same scale as the corresponding 3D mesh of the physical component (Figure 14). Next, each VAM component quadrilateral is manually oriented and positioned in front of the corresponding real component's 3D mesh; specifically, the side of the component that the user looks at the most. For example, the flowmeters' VAM icon is laid over the real flowmeter tubes. The icon is placed where users read the gas levels on the front of the machine, rather than on the back of the machine where users rarely look. Note that there are many other approaches to this challenge (e.g., texturing the machine model itself or using more complex 3D models of the diagram rather than texture-mapped 3D quadrilaterals) that we may investigate in the future.

Fig. 15. The three states of the mechanical ventilator controls.

6.1.2 *Visual Overlay*. Once the problem of transforming a 2D diagram to a 3D object is addressed, another challenge is how to display the transformed diagram in the same context as the 3D mesh of the physical component so that the student can perceive it and learn from it, regardless of spatial ability. For example, the diagram and the physical component's mesh could be alpha blended (i.e., linear interpolation of colors to enable a transparency effect) together. Then the user would be able to visualize both the geometric model and the diagrammatic model at all times. However, in the case of the AAM, alpha blending would create additional visual complexity that could be confusing to the user and hinder the learning experience. For this reason, the VAM icon quadrilaterals are opaque. They occlude the underlying physical component geometry. However, since users interact in the space of the real machine, they can look behind the tablet PC to observe machine operations or details that may be occluded by VAM icons.

6.1.3 *Simulation States and Data Flow*. There are many internal states of an anesthesia machine that are not visible in the real machine. Understanding these states is vital to understanding how the machine works. The VAM shows these internal state changes as animations so that the user can visualize them. For example, the VAM ventilator model has three discrete states (Figure 15): (1) off, (2) on and exhaling, and (3) on and inhaling. A change in the ventilator state will change the visible flow of data (e.g., the flow of gases).

Similarly, the AAM uses animated icons (e.g., change in the textures on the VAM icon quadrilaterals) to denote simulation state change. To minimize spatial complexity, only one state per icon is shown at a point in time. The current state of an icon corresponds to the flow of the animated 3D gas particles and helps students to better understand the internal processes of the machine.

6.1.4 *Diagrammatic Graph Arcs Between Components*. Students may also have problems with understanding the functional relationships between the real machine components. In the VAM, these relationships are visualized with 2D pipes. The pipes are the arcs through which particles flow in the VAM gas flow model. In the AAM, the 3D layout is more complex, therefore the arc geometry is more complex too. We take steps to simplify these arcs in 3D.

As in the VAM, the AAM's pipes are not collocated with the real pneumatic connections inside the physical machine but conversely the arcs are 3D cylinders instead of 2D. To make visualization simpler, the pipes in the AAM intersect with neither the machine geometry nor with other pipes. In the case that some of the arcs appear to visually cross each other from certain perspectives, the overlapping sections of the pipes are assigned different colors to facilitate the 3D data flow visualization. These design choices are meant to enable students to visually trace the 3D flow of gases in the AAM.

6.1.5 *Magic Lens Display: See-Through Effect.* For enhanced learning, our approach aims to put the diagram-based, dynamic, transparent reality model in the context of the real machine using a see-through magic lens. For the see-through effect, the lens displays a scaled high-resolution 3D model of the machine that is registered to the real machine. There are many reasons why the see-though functionality was implemented with a 3D model of the machine registered to the real machine. This method was chosen over a video see-though technique (prevalent in many mixed reality applications) in which the VAM components would be superimposed over a live video stream. The two main reasons for a 3D model see-through implementation are as follows.

(1) To facilitate video see-through, a video camera would have to be mounted to the magic lens. Limitations of video camera field of view and positioning make it difficult to maintain the magic lens' window metaphor.
(2) Using a 3D model of the machine increases the visualization possibilities. For example, the real machine cannot be easily deconstructed due to physical constraints but a modeler can use 3D modeling software to interactively deconstruct and spatially reorganize the 3D model. This facilitates visualization in the VAM-context method and the visual transformation between the VAM-context and real machine-context methods as described in the previous section.

There are many other types of displays that could be used to visualize the VAM superimposed over the real machine (such as see-though Head-Mounted Display (HMD)). The lens was chosen because it facilitates both VAM-context and real machine-context visualizations. More immersive displays (i.e., HMDs) are difficult to adapt to the 2D visualization of the VAM-context without obstructing the user's view of the real machine. However, as technology advances, we will reconsider alternative display options to the magic lens.

6.1.6 *Tracking the Magic Lens Display.* The next challenge is to display the contextualized model to the user from a first-person perspective and in a consistent space. As stated, our approach utilizes a magic lens that can be thought of as a "window" into the virtual world of the contextualized diagrammatic model (see Section 4.1 of the online supplement for additional explaination of the magic lens window metaphor).This requires tracking the position and orientation of the magic lens. The AAM tracking system uses a computer vision technique called outside-looking-in tracking (Figure 16). The tracking method is widely used by the MR community and is described in more detail in van Rhijn [2005]. The technique consists of multiple stationary cameras that observe special markers that are attached to the objects being tracked (in this case the object being tracked is the tablet PC that instantiates the magic lens). The images captured by the cameras can be used to calculate positions and

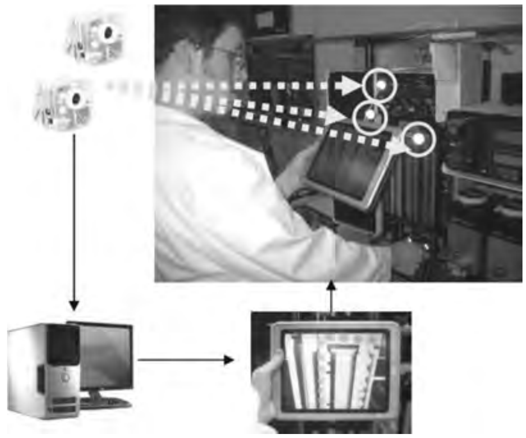

Fig. 16. A diagram of the magic lens tracking system.

orientations of the tracked objects. The cameras are first calibrated by having them all view an object of predefined dimensions. Then the relative position and orientation of each camera can be calculated.

After calibration, each camera must search each frame's images for the markers attached to the lens; then the marker position information from multiple cameras is combined to create a 3D position. To reduce this search, the AAM tracking system uses cameras with infrared lenses and retro-reflective markers that reflect infrared light. Thus, the cameras see only the markers (reflective balls in Figure 16) in the image plane. The magic lens has three retro-reflective balls attached to it. Each ball has a predefined relative position to the other two balls. Triangulating and matching the balls from at least two camera views can facilitate calculation of the 3D position and orientation of the balls. Then this position and orientation can be used for the position and orientation of the magic lens.

The tracking system sends the position and orientation over a wireless network connection to the magic lens. Then, the magic lens renders the 3D machine from the user's current perspective. Although tracking the lens alone does not result in rendering the exact perspective of the user, it gives an acceptable approximation as long as users know where to hold the lens in relation to their head. To view the correct perspective in the AAM system, users must hold the lens approximately 25cm away from their eyes and orient the lens perpendicular to their eye gaze direction. To accurately render the 3D machine from the user's perspective independent of where the user holds the lens in relation to the head, both the user's head position and the lens must be tracked. Tracking both the head and the lens will be considered in future work.

6.2 Interaction Contextualization

Our approach allows the user to interact with the physical phenomenon that is used as a real-time interface to the dynamic model. The main challenge here is how to engineer systems for synchronizing the user's physical device interaction with the dynamic model's inputs.

Table I. Methods of Tracking Various Machine Components

Machine Component	Tracking Method
Flowmeter knobs	IR tape on knobs becomes more visible as knob is turned. IR webcam tracks 2D area of tape. (Figure 16)
APL Valve Knob	Same method as flowmeters.
Manual Ventilation Bag	Webcam tracks 2D area of the bag's color.
Airway Pressure Gauge	Webcam tracks 2D position of the red pressure gauge needle.
Mechanical Ventilation Toggle Switch	Connected to an IR LED monitored by an IR webcam.
Flush Valve Button	Membrane switch on top of the button and connected to an IR LED monitored by and IR webcam
Manual/Mechanical Selector Knob	2D position of IR tape on toggle knob is tracked by an IR webcam.

6.2.1 *Using the Physical Machine as an Interface to the Dynamic Model.* To address the challenge of synchronizing the model with the physical device, the AAM tracking system tracks the input and output (i.e., gas flowmeters, pressure gauges, knobs, buttons) of the real machine and uses them to drive the simulation. For example, when the user turns the O_2 knob to increase the O_2 flow rate, the tracking system detects this change in knob orientation and sends the resulting O_2 level to the dynamic model. The model is then able to update the simulation visualization with an increase in the speed of the green O_2 particle icons.

A 2D optical tracking system with 4 webcams driven by OpenCV [Bradski 2000] is employed to detect the states of the machine (see online supplement Section 4.2 for a screenshot). State changes of the input devices are easily detectable as changes in 2D position or visible marker area, as long as the cameras are close enough to the tracking targets to detect the change. For details and examples of how each component was tracked, refer to Table I (for implementation details and figures of AAMs for other anesthesia machines, see online supplement Section 4.3).

6.3 Hardware

This section outlines the hardware used to meet the challenges of visual and interaction contextualization. The system consists of three computers: (1) the magic lens is an HP tc1100 Tablet PC, (2) a Pentium IV computer for tracking the magic lens, and (3) a Pentium IV computer for tracking the machine states. These computers interface with six 30 Hz Unibrain Fire-I webcams. Two webcams are used for tracking the lens. The four other webcams are used for tracking the machine's flowmeters and knobs. The anesthesia machine is an Ohmeda Modulus II. Except for the anesthesia machine, all the hardware components are inexpensive and commercial off-the-shelf equipment.

7. EVALUATING CONTEXTUALIZATION: A HUMAN STUDY

To evaluate our contextualization approach and investigate the learning benefits of contextualization in general, we conducted a study in which 130 psychology students were given one hour of anesthesia training using one of

5 simulations: (1) the VAM, (2) a stationary desktop version of the AAM with mouse-keyboard interaction (AAM-D), (3) the AAM, (4) the physical anesthesia machine with no additional simulation (AM), and (5) an interactive, desktop PC version of a photorealistic anesthesia machine depiction with mouse-based interaction (AM-D).

Hypothesis: A *contextualized* diagram-based dynamic model will compensate for users' low spatial cognition more effectively than other types of models (e.g., the VAM).

The study was conducted in several iterations throughout 2007 and 2008. Parts of this study were previously reported [Quarles et al., 2008a, 2008b, 2008c]. In this section, these previous results are summarized and extended with results from additional conditions and analyses that pertain specifically to the spatial mapping problems experienced when transitioning from the VAM to the real machine.

7.1 Study Procedure Summary

For each participant, the study took place over two days.

DAY 1 (∼90 min).

(1) *1 hour of training in anesthesia machine concepts using one of the 5 simulations.*
(2) S*patial ability testing*: Participants were given three general tests to assess their spatial cognitive ability at three different scales [Montello 1993]: The Arrow Span Test (small scale), The Perspective Taking Test (medium scale), and the Navigation of a Virtual Environment Test (large scale). Each of these is taken from cognitive psychology literature [Huttenlocher and Presson 1973; Just and Carpenter 1985; Moffat et al. 1998]. Each of these scales corresponds to different types of spatial challenges and thus requires different tests for assessment. Detailed descriptions of how and why one would conduct these test is explained in Hegarty et al. [2006].

DAY 2 (∼90 min).

(1) *Matching the Simulation Components to Real Machine Components*: To assess VAM-icon-to-machine mapping ability, participants were shown two pictures: (1) a screenshot of the training simulation (e.g., AAM or VAM) and (2) a picture of the real machine. Participants were asked to match the simulation components (e.g., icons) in picture (1) to the real components in picture (2). Note that AM and AM-D did not complete this test because the answers would have been redundant (i.e., we assumed that if participants were shown two of the same pictures of the machine, they would be able to perfectly match components between the pictures).
(2) *Written tests*: The purpose of this test was to assess abstract knowledge gained from the previous day of training. The test consisted of short-answer and multiple-choice questions from the Anesthesia Patient Safety Foundation anesthesia machine workbook [Lampotang et al. 2007]. Participants did not use any simulations to answer the questions. They could only use their machine knowledge and experience.

Table II. Self-Reported Difficulty in Visualizing Gas Flow (DVGF)

Group	Average	Stdev
AAM	3.79	1.72
VAM	5.28	2.13
AM	5.50	1.91
AM-D	5.41	2.18
AAM-D	5.52	2.10

Table III. Analysis of DVGF Variance (significant differences)

Groups Compared	p value
AAM – AM	p = 0.01
AAM – VAM	p = 0.05
AAM – AM-D	p = 0.04
AAM – AAM-D	p = 0.01

(3) *Fault test*: A "hands-on" test was used to assess participant's procedural knowledge gained from the previous day of training. For this test, participants used only the anesthesia machine without any type of computer simulation. The investigator first caused a problem with the machine (i.e., disabled a component). Then the participant had to find the problem and describe what was happening with the gas flow.

(4) *Self-Reported Difficulty in Visualizing Gas Flow (DVGF)*: When participants had completed the hands-on test, the investigator explained what it meant to mentally visualize the gas flow. Participants were then asked to self-rate how difficult it was to mentally visualize the gas flow in the context of the real machine on a scale of 1 (easy) to 10 (difficult).

7.2 Results and Discussion

Note: for Pearson correlations, the significance is marked as follows: * is $p < 0.1$,** is $p < 0.02$,*** is $p < 0.01$.

7.2.1 *Discussion of DVGF*. Results suggest that the AAM significantly improved gas flow visualization ability (Table II, where lower scores indicate improved self-reported ability, and Table III). The AAM likely compensated for low spatial cognition more effectively than AAM-D. This could be due to the interaction style that the magic lens affords.

The correlations (i.e., Table IV) can be interpreted as follows. Higher DVGF scores mean the participant had greater difficulty visualizing gas flow. For the Arrow span test, the best score was 60, and decreasing scores denotes lower small-scale ability. For large-scale ability, the best sketch map score was 0, and increasing scores denote lower large-scale ability. For example in Table IV, the VAM Group's Sketch maps had a +0.61 correlation to their self-reported DVFG scores. This means that when a VAM user finds it more difficult to visualize gas flow (DVGF) then they also tend to have a lower large-scale spatial ability.

Results suggest that AAM and AAM-D participants' spatial cognition had minimal impact on gas visualization ability (Table IV). Note that both of these

Table IV. DVGF Correlations to Spatial Cognition Tests

Group	Arrow Span	Nav. Sketch Map
AAM	+0.01	−0.06
VAM	−0.40*	+0.61***
AM	−0.53***	+0.16
AM-D	−0.02	−0.30
AAM-D	+0.12	−0.04

Table V. Written Test Scores correlations to Spatial Cognition Tests

Group	Arrow Span	Nav. Sketch Map
AAM	+0.17	−0.33
VAM	+0.32	−0.50**
AM	+0.61***	−0.23
AM−D	+0.13	−0.08
AAM-D	−0.19	−0.38

conditions utilized contextualization in that the VAM components were mapped to a geometric model of the real machine. The main difference between these two conditions was that in the AAM condition, the geometric model was contextualized with the real machine. In both cases, spatial cognition minimally affected gas flow visualization ability. This suggests that the contextualization method of superimposing abstract models over physical (or photorealistic, in the case of the AAM-D) phenomena may compensate users with low spatial cognition.

7.2.2 *Discussion of Written Tests.* The correlations between written tests and spatial cognition tests (Table V) can be interpreted as follows. On the written test, a higher score denotes a better understanding of the information. This is correlated in the VAM and AM groups to spatial ability. For example, when a VAM user has a higher large-scale ability score, they tend to better understand the information (higher written test score). A similar effect in small-scale ability can be found with the AM group.

Results suggest that AAM and AAM-D participants' spatial cognition had lesser impact on written test performance (Table V) than the types of simulation. The written test was a measure of participant understanding of anesthesia concepts. In the case of AAM and AAM-D, lower levels of spatial cognition skill did not impede their understanding as appeared to be the case in the VAM and AM groups. This suggests that the contextualization method of superimposing abstract models over physical (or photorealistic, in the case of the AAM-D) phenomena may compensate users with low spatial cognition when users are presented with complex concepts.

7.2.3 *Discussion of Matching.* Matching is a measure of ability to map the simulation components to the real phenomenon. Results suggest that AAM significantly ($p = 0.04$) improved matching ability (Table VI). Note that this matching test is likely related to the spatial mapping problem described in Section 1. This suggests that the AAM's contextualization method is an effective means of addressing this mapping problem.

Table VI. Matching (summarized from Quarles et al. [2008c])

Group	Average Score	Stdev
VAM	2.56	0.95
AAM-D	2.50	0.99
AAM	3.12	0.84

Table VII. Matching Correlations to Arrow Span Test

VAM	0.63***
AAM-D	0.37
AAM	0.29

One reason for this improvement may be that the AAM compensated for low spatial cognition (Table VII). In the AAM, spatial cognition test scores were significantly (using Fisher r-to-z transformation, $p = 0.06$) less correlated to the matching scores than the VAM. VAM participants that scored lower in the matching had lower spatial ability. This suggests that the AAM compensates for low spatial cognition and that our MR-based contextualization approach may be effective in addressing the spatial mapping problem.

8. CONCLUSIONS AND FUTURE WORK

This article presented and evaluated a MR-based method of contextualizing diagram-based dynamic models with the real phenomena being simulated. To interactively visualize this contextualization, we used MR technology such as a magic lens and tracking devices. The magic lens allows users to visualize the VAM superimposed into the context of the real machine from a first-person perspective. The lens acts as a window into the world of the overlaid 3D VAM simulation. In addition, MR technology combines the simulation visualization with the interaction of the real machine. This allows users to interact with the real machine and visualize how this interaction affects the dynamic, transparent reality model of the machine's internal workings.

The main innovations of this research are: (1) the method of blending dynamic models with the real phenomena being simulated through combining visualization and interaction and (2) the evaluation of this method. The results of our evaluation suggest that MR-based contextualization compensates for low spatial cognition and thereby enhances the user's ability to understand the mapping between the dynamic model and the corresponding real phenomenon. In the future, we will work to engineer a general software framework that aids application developers (i.e., educators rather than MR researchers) in combining dynamic models and real-world phenomena.

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