Understanding of Anesthesia Machine Function Is Enhanced With a Transparent Reality Simulation

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Introduction: Photorealistic simulations may provide efficient transfer of certain skills to the real system, but by being opaque may fail to encourage deeper learning of the structure and function of the system. Schematic simulations that are more abstract, with less visual fidelity but make system structure and function transparent, may enhance deeper learning and optimize retention and transfer of learning. We compared learning effectiveness of these 2 modes of externalizing the output of a common simulation engine (the Virtual Anesthesia Machine, VAM) that models machine function and dynamics and responds in real time to user interventions such as changes in gas flow or ventilation.

Methods: Undergraduate students ($n = 39$) and medical students ($n = 35$) were given a single, 1-hour guided learning session with either a Transparent or an Opaque version of the VAM simulation. The following day, the learners' knowledge of machine components, function, and dynamics was tested.

Results: The Transparent-VAM groups scored higher than the Opaque-VAM groups on a set of multiple-choice questions concerning conceptual knowledge about anesthesia machines ($P = 0.009$), provided better and more complete explanations of component function ($P = 0.003$), and were more accurate in remembering and inferring cause-and-effect dynamics of the machine and relations among components ($P = 0.003$). Although the medical students outperformed undergraduates on all measures, a similar pattern of benefits for the Transparent VAM was observed for these 2 groups.

Conclusions: Schematic simulations that transparently allow learners to visualize, and explore, underlying system dynamics and relations among components may provide a more effective mental model for certain systems. This may lead to a deeper understanding of how the system works, and therefore, we believe, how to detect and respond to potentially adverse situations.

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Key Words: Anesthesia, Transparent simulation, Learning, Undergraduates, Medical students, Anesthesia machine

The anesthesia machine is a complex piece of life support equipment because its plumbing is generally hidden from view. Even if the plumbing is made visible and transparent, the gases are colorless and invisible and therefore hard to trace through the system. Further, the effects of different controls, and their interactions on gas flow, composition, volume, and pressure are not visible and may not be evident to learners. Others have attempted to address this learning need by creating anesthesia machine learning aids, including computer animations of machine faults,[1] simulations of the breathing circuit (*BreathSim*[2]), and an online manual (*Explore!*[3]).

The original Virtual Anesthesia Machine simulation (VAM, about 1999) was designed to facilitate learning about the anesthesia machine and its function by providing direct, interactive visualization of gas flows, concentrations, and volumes.[4] This "transparent reality" simulation technique used by the original VAM renders the invisible visible, providing a mental model designed to make the abstract concrete and the complex simple to visualize and understand.[5] VAM is currently available free of charge worldwide in 23 languages and 6 medical gas color codes at http://vam.anest.ufl.edu/wip.html. VAM is used via standard Web browsers such as Microsoft Internet Explorer after installing the free Adobe Shockwave and Flash players. VAM is used in more than 300 institutions and programs worldwide (including the University of Florida anesthesia residency program) and has been well received. A grayscale screenshot of the Transparent-VAM simulation is shown in Figure 1A.

One hypothesis is that VAM has been well accepted by learners because it provides more efficient and effective learning through a transparent reality simulation. To test the hypothesis, we created an opaque simulation of an anesthesia machine with Director (Adobe Systems Inc, San Jose, CA), using a simulation engine (mathematical models and scripts) identical to that of the Transparent Reality VAM. The opaque simulation was externalized mainly via a photographic image of a Modulus II (Ohmeda, Madison, WI) anesthesia machine

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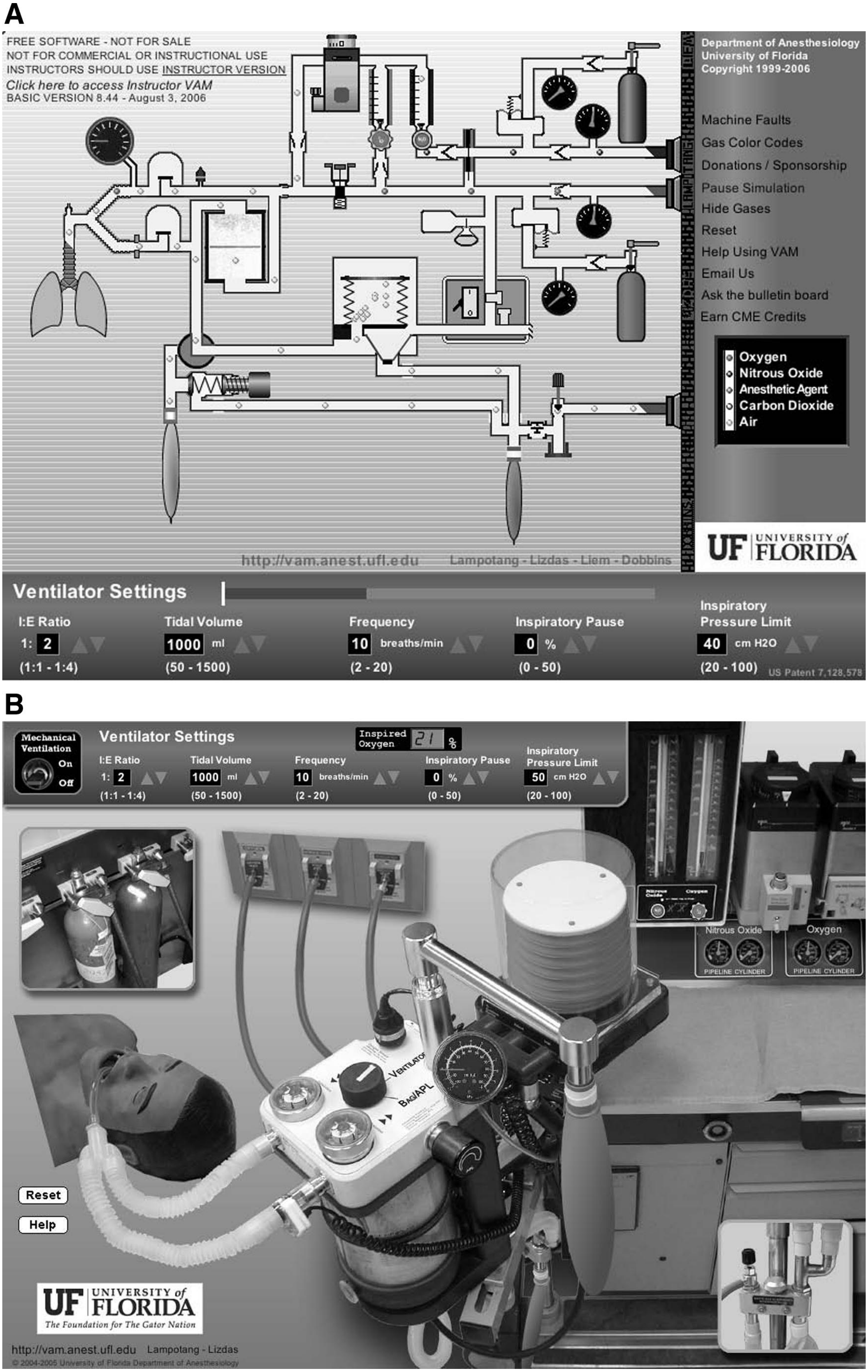

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Ventilator Settings

I:E Ratio 1: 2 (1:1 - 1:4)
Tidal Volume 1000 ml (50 - 1500)
Frequency 10 breaths/min (2 - 20)
Inspiratory Pause 0 % (0 - 50)
Inspiratory Pressure Limit 40 cm H2O (20 - 100)

Ventilator Settings

Inspired Oxygen 21 %
I:E Ratio 1: 2 (1:1 - 1:4)
Tidal Volume 1000 ml (50 - 1500)
Frequency 10 breaths/min (2 - 20)
Inspiratory Pause 0 % (0 - 50)
Inspiratory Pressure Limit 50 cm H2O (20 - 100)

Figure 1. Screen shots from the Transparent (A) and Opaque (B) Virtual Anesthesia Machine (VAM) simulations.

taken from a typical anesthesia provider perspective. All user adjustable components such as the ventilator controls and oxygen flush were made interactive, acting as inputs to the simulation engine. Only outputs visible to the naked eye such as movement of the bellows and pressure gauge needles were reproduced. A grayscale screenshot of the Opaque simulation is shown in Figure 1B. Both the Opaque and the Transparent VAM simulations are currently available free of charge at http://vam.anest.ufl.edu/wip.html.

In the Transparent simulation, the "plumbing" is depicted explicitly, gases and gas flow are represented as colored particles flowing and mixing through the plumbing and machine components, and the state and operation of various controls and other components are made visible (eg, one can readily assess the position of the bag/ventilator selector switch by simply looking at the gas flow path that is being allowed). We might expect, then, that a transparent simulation that makes these attributes and dynamics visible and interactive may be particularly helpful in fostering understanding of machine structure and function.

We also compared the effectiveness of these 2 kinds of simulation among 2 groups of participants. It has long been known that expertise in an appropriate domain may enhance not just the "quantity" but the "quality" of learning in that domain.[6] However, because even novice residents and clinicians would have been exposed in differing degrees to aspects of anesthesia machines that could compromise the evaluation, we chose to compare medical students to young undergraduates with interest in healthcare profession studies.

METHODS

To objectively evaluate the relative effectiveness of the Transparent and Opaque VAM versions as learning tools, we gave students a single, workbook-guided learning session that first introduced them to the principles and goals of the anesthesia machine. Students were then led through 5 interactive exercises with either the Transparent or the Opaque VAM. Learning was assessed the following day with both objective and self-report measures. The objective measures were intended to test diverse aspects of knowledge about the machine, from the identity of specific components, to the interactive function of several subsystems. They included knowledge that was presented explicitly, as well as that which could be inferred from an understanding of the machine function. We expected that the Opaque version might provide better ability to identify system components, and perhaps to explain their primary function. The Transparent version, however, would provide significantly better performance on questions relating to explicit or inferred relations and interactions between components, and those relating to overall system function and troubleshooting. Finally, we expected that subjective measures would indicate greater confidence in understanding after training with the Transparent version, and greater preference for the transparent version after exposure to the alternative format.

Our study was approved by the University of Florida Institutional Review Board for social and behavioral sciences (IRB02, protocol #2006-U-573). Two groups of students participated. Undergraduate students enrolled in General Psychology classes at the University (n = 39) who were taking a prehealth profession curriculum participated in the study as part of a course requirement. Additionally, first-year medical students (n = 35) participated and were given movie passes as incentives. Those who indicated any prior knowledge about the anesthesia machine were to be excluded from the study, but none indicated any such knowledge. Students were alternately assigned to either an Opaque or a Transparent simulation group by the order in which they were run.

Two versions (Opaque and Transparent) of a workbook were developed that introduced students to the general purpose and overall structure of the anesthesia machine, indicating its major subsystems and control features. The Opaque workbook was used by students assigned to the Opaque-VAM groups and the Transparent workbook by those in the Transparent-VAM groups. The assigned workbook directed students through a "functional tour" of the operation of the machine, requiring students to work with their assigned simulation to learn about several of the basic subsystems of the machine, namely the breathing circuit, mechanical ventilation, and manual ventilation. The workbooks were modeled after the free Anesthesia Patient Safety Foundation anesthesia machine workbook, a companion learning aid to the VAM simulation.[7]

The workbooks differed slightly because they referred to the 2 different simulation formats. We tried to make them as similar as possible in style and content, and to make the factual information provided essentially identical. Both encouraged students to make use of the respective simulations as they progressed through the workbook.

The subsequent 5 sections were each organized around a specific question regarding machine function, for example: *Are the gases exhaled by a patient "scrubbed" of CO_2 before entering the bellows during mechanical ventilation?* The student was then led through a series of operations with the assigned simulation to observe conditions and changes relevant to the question. Throughout these steps, questions were posed that required inspection of the assigned simulation. At the end of the section, the correct answer to the question was reviewed (in this case, *No*), and the rationale given, which was intended to encourage a revisualization of the process. The opaque and transparent versions of the workbooks used for the study are available at http://vam.anest.ufl.edu/handout/studyworkbooks.html.

Assessment of learning was not conducted until the day following the learning session. Because learning with understanding is associated with more enduring retention,[8] and immediate tests are more likely to reflect superficial, verbatim recall,[9] we thought that a retention interval of about 24 hours would be more likely to reveal any differences in learning. Pilot work with undergraduate students also suggested that the 24-hour retention interval was associated with intermediate levels of performance, thus minimizing either ceiling or floor effects on the various measures that would compromise the comparisons between groups.

In the assessment phase, students first had to name various components (eg, the *adjustable pressure-limiting valve*, or APL) from screen shots of their simulation, and explain their

Table 1. Mean Performance on Four Dependent Learning Measures (see text for definitions) Across Simulation Type (Transparent or Opaque) and Educational Level (Undergraduates or Medical Students)

	Component Naming	Component Function	System Dynamics	Multiple-Choice Review Questions
Medical students				
Transparent simulation	3.12 (0.17)	3.29 (0.15)	2.64 (0.16)	0.62 (0.04)
Opaque simulation	2.93 (0.18)	3.05 (0.16)	2.29 (0.13)	0.49 (0.04)
Undergraduates				
Transparent simulation	2.03 (0.17)	2.34 (0.15)	1.90 (0.12)	0.46 (0.04)
Opaque simulation	1.67 (0.17)	1.64 (0.14)	1.47 (0.12)	0.37 (0.04)

Standard errors are given in parentheses.

Maximum possible score for component naming and function, and system dynamics, was 4.00; maximum score on the review questions was 1.00.

function. These images depicted the entire system, as seen in Figures 1A and B, with the tested component circled and labeled.

Students then answered a set of 22 short-answer questions about system dynamics intended to require a deeper understanding of specific machine functions (eg, *Why are there 2 separate pipelines leading to the scavenging system? If the Adjustable Pressure Limiting (APL) valve is adjusted during mechanical ventilation, what is the effect on the amount of gas flow into the CO_2 absorber?*). Answers were sometimes directly or indirectly studied the preceding day, or (with 8 of the 22 questions) could be inferred from what was studied. In all cases, importantly, the questions could in principle be answered fully by information presented in the assigned workbooks alone. Students also rated their confidence in all their written answers (component function and system dynamics), on a 0 to 4 Likert scale.

These questions were followed by a set of 8 multiple-choice questions that were adapted from published review guides commonly used by anesthesiologists. The selected questions emphasized concepts and procedures that are required for safe and efficient operation of an anesthesia machine. Answers to these questions could also be found in the assigned workbooks.

Following all the assessments, students were shown the alternative (nonassigned) simulation format, were allowed to briefly explore the simulation, and then asked which of either they would prefer for future learning about the anesthesia machine.

Two of us (D.E.L. and S.L.) provided answers to the questions that required a written response, indicating cases where alternative answers were satisfactory. Six undergraduate research assistants read through these answers, and then practiced scoring on 2 of the student protocols, using a scale of 4 = full credit, to 0 = no credit. Discrepancies in scoring were discussed during training sessions. Two assistants then scored the responses of each student, being blind as to the simulation group. In fewer than 10% of the cases were these ratings different by more than one point; in any case, the average of the 2 raters was used as the score for a particular response.

RESULTS

Performance Measures

For each of the 4 objective measures of performance, a single score was derived for each participant by averaging their scores on the individual questions. Mean scores across subjects for all conditions are presented in Table 1. A multivariate 2×2 factorial ANOVA was performed on these data, with simulation type (Transparent versus Opaque VAM) and educational level (undergraduate versus medical student) as between-group independent variables. Effects with $\alpha < 0.05$ were considered significant. Hotelling's T was used to determine significance, and strength of effects was estimated by the η^2 statistic (see Appendix for a brief explanation of these statistics).

In the overall analysis, there were significant main effects for simulation type (Hotelling's $T = 0.270$, $F(4,67) = 4.52$, $P = 0.003$, partial $\eta^2 = 0.213$) and for education level (Hotelling's $T = 0.937$, $F(4,67) = 14.71$, $P < 0.001$, partial $\eta^2 = 0.484$). Critically, the interaction of simulation type and educational level did not approach significance (Hotelling's $T = 0.069$, $F(4,67) = 1.14$, $P = 0.342$, partial $\eta^2 = 0.064$).

The significant multivariate analysis of variance (MANOVA) results for the effect of simulation type were followed by univariate ANOVAs on each of the dependent variables. In each case, the main effect of education level was significant, with the medical students outperforming the undergraduates. However, as implied by the overall MANOVA, in no case did educational level interact with simulation type.

Identification of Components

Contrary to our expectations, the Opaque-VAM groups did not do better than the Transparent-VAM groups at identifying components. In fact, the Transparent groups had slightly, though not significantly, better accuracy of component naming ($Mt = 2.56$, $Mo = 2.24$; $F(1,70) = 2.55$, $P = 0.115$, partial $\eta^2 = 0.035$).

Describing Component Function

The Transparent-VAM groups provided better explanations of component function. The difference ($Mt = 2.80$, $Mo = 2.29$) was significant ($F(1,70) = 9.51$, $P = 0.003$, partial $\eta^2 = 0.120$).

Written Responses to Questions About System Dynamics

The Transparent-VAM groups provided significantly better answers to the questions about system dynamics ($Mt = 2.21$, $Mo = 1.84$, $F(1,70) = 9.65$, $P = 0.003$, partial $\eta^2 = 0.121$).

The questions about system dynamics varied widely in difficulty, as judged by overall accuracy of answers across participants. Because these questions were intended to test for a deeper, more thorough understanding of cause-and-effect relations among machine components and subsystems, a follow-up analysis was done by splitting the questions into relatively easier versus harder questions, above and below the median score for overall accuracy. A multivariate 2 × 2 factorial ANOVA was performed on these data. Following a significant overall effect of simulation type on performance (Hotelling's $T = 0.220$, $F(2,69) = 7.60$, $P = 0.001$, partial $\eta^2 = 0.181$), univariate tests showed that there was no effect of simulation type for the easier questions ($Mt = 2.86$, $Mo = 2.60$, $F(1,70) = 1.74$, $P = 0.102$, partial $\eta^2 = 0.038$), but a large and significant effect of simulation type for the harder questions ($Mt = 1.66$, $Mo = 1.09$, $F(1,70) = 14.95$, $P < 0.001$, partial $\eta^2 = 0.176$).

Multiple Choice Questions

The Transparent-VAM groups were significantly more accurate on the multiple-choice questions ($Mt = 53\%$, $Mo = 42\%$ correct; $F(1,70) = 7.24$, $P = 0.009$, partial $\eta^2 = 0.094$).

Subjective Measures

Confidence Ratings

Mean confidence ratings were obtained for each participant across questions for their answers about component function, and system dynamics. A multivariate 2 × 2 factorial ANOVA was performed on these data. The Transparent-VAM groups tended to report higher confidence in their answers than did the Opaque-VAM groups, but the overall effect of simulation type was not significant in the multivariate test (Hotelling's $T = 0.169$, $F(4,98) = 2.07$, $P = 0.09$, partial $\eta^2 = 0.078$).

Preferences

After their brief interaction with the alternative format for the simulation, almost all of the undergraduate students in the Transparent-VAM groups (seventeen of twenty) still preferred the Transparent-VAM simulation, which they had been assigned to work with the previous day, and only one preferred the Opaque simulation. Two undergraduates indicated that they would prefer being able to use both kinds of simulation for subsequent study. Remarkably, the majority (eleven) of the undergraduate Opaque group also indicated a preference not for the more familiar, concrete and practiced Opaque simulation, as one might expect, but for the Transparent-VAM simulation. Seven preferred the Opaque simulation, and 2 indicated a preference for both.

Among the medical students, the Transparent group preferred the Transparent VAM over the Opaque version (9 vs. 4), with five wanting both. Five students who had trained with the Opaque simulation nonetheless chose the Transparent VAM, while 5 preferred the Opaque version. Seven students in this group wanted to work with both. In contrast to the undergraduates, then, preferences were more balanced, and more medical students than undergraduates in both simulation groups thought that experience with both kinds of simulation would be optimal.

In all groups, those who preferred the transparent version stressed the value of being able to see the dynamic functioning and flow of gasses; those who preferred the opaque version stressed how the realistic appearance would help in locating controls on a real machine, and provide a physical context that could aid learning of more abstract aspects of machine function.

DISCUSSION

On 3 of the 4 objective measures of learning, working with the Transparent Reality VAM simulation produced a significant advantage, compared with working with the photorealistic but Opaque VAM simulation. A trend toward superior performance by the Transparent-VAM group was seen even for aspects of the system that would seem most amenable to learning with concrete, visually realistic depictions (naming of components). Importantly, the 2 measures on which the Transparent-VAM group had the largest advantage were those that were intended to test a deeper, more systematic understanding of the anesthesia machine: those about component purpose and function, and the questions about interactive dynamics among system components. Moreover, the differences were greatest for the more difficult questions about cause-and-effect dynamics and relations. Providing students with a more abstract and schematic but transparent simulation of a system— one that makes the underlying dynamics of the system and integrative function of its components concrete and visible—appears to produce a more effective, and we believe enduring, learning experience.

The absolute size of the advantage for the Transparent VAM was in some respects modest, as were the measures of association (partial η^2 typically in the 0.10–0.20 range). But, it should be remembered that the workbooks themselves provided enough information to answer all the questions, and so the effect of the Transparent VAM was obtained in the face of that common foundation of available information. Second, in some cases at least the percent gain for the Transparent VAM over the Opaque VAM was substantial—for the harder questions about dynamics, it was 33% for the medical students, and 83% for the undergraduates; for the multiple-choice questions, the respective percent gains were 24% and 27%.

Providing gains of that size should be of interest to educators and anesthesia machine manufacturers, especially in light of its potential impact on patient safety. User error was 3 times more common than equipment failure in closed claims (most due to death and permanent brain damage) associated with gas delivery equipment.[10] Effective educational and training techniques may have the most potential to reduce human error and improve the safety of anesthesia equipment. Transparent-reality simulations are inherently more labor-intensive to develop (because eg, internal gas flows have to be explicitly and graphically represented), but if follow-up studies do confirm more effective learning in actual anesthesia machine users, then the added cost may well be justified.

It was somewhat surprising to us that the Opaque-VAM groups did not do better than Transparent-VAM groups in simply identifying/naming machine components. It does seem likely that the Opaque group would show greater transfer of learning of both component identity and location to the actual Ohmeda Modulus II machine. But, it is unclear whether any such advantage would be seen when faced with other machines, which can have radically different physical appearances.

The present study is not the first to systematically compare these 2 radically different kinds of simulation on learning conceptual knowledge about a complex system. But, it is, we believe, the first to make the comparison with this degree of control over the underlying simulation engine, the supporting textual material, and the step-by-step sequence of operations and observations the learner is guided through. Nonetheless, being able to see the "hidden processes" as the system is studied appears to provide significantly more effective learning.

The potential value of such abstract, but functionally transparent, representations for simulations has been understood for some time by psychologists, educators and trainers.[11–14] Various terms have been offered, including *physical fidelity* versus *conceptual fidelity*, *iconic* versus *schematic,* [15] *concrete* versus *idealized* or *abstract* [16] or *experiential* versus *symbolic*.[17] None of these terms seems to fully capture the difference between the 2 forms of the VAM, however. For example, the Transparent VAM is a more abstract representation (in terms of visual fidelity) of the physical system, but it makes certain abstract dynamic properties of the physical system (such as the plumbing layout and gas flow) more concrete and explicit. Transparent simulations reveal, in real time and under interactive control, the physical and mechanical functioning of a complex mechanical system.

Previous studies have compared schematic but transparent representations, on the one hand, to photorealistic but opaque representations of complex physical systems. Although this work generally shows more effective learning with transparent representations, results have been mixed. This is perhaps not surprising given the variety of tasks, learners and outcome measures that have been employed. Moreover, with few exceptions, these studies have used static drawings and illustrations, rather than dynamic animations or interactive simulations.[15,18–20] We might expect that the ability to interactively explore the dynamics of such simulations would be particularly effective for developing an understanding of underlying system behavior and principles.

The transparent reality simulation provided comparable advantages for the medical students and undergraduates. The lack of any interaction of simulation type with educational level is surprising, and impressive. The undergraduates were, for the most part, freshmen and sophomores, many of whom will ultimately engage in careers other than in the health sciences. Even the medical students are still some distance from those who are the ultimate audience for the transparent VAM, and extrapolation to residents and clinicians must be done cautiously. But, these findings encourage us to think that similar advantages will be found even in more advanced and knowledgeable groups of learners.

Just as important for educational practice would be to determine whether the Transparent VAM group would also demonstrate better procedural skill in using a real anesthesia machine—managing an anesthetic, monitoring patient response, detecting unsafe conditions and machine faults, and responding effectively to these events. Troubleshooting is perhaps the most important area where the "deep knowledge" can provide an advantage over other kinds of declarative or procedural knowledge about a system. We hope to explore this question at the Center for Simulation and Advanced Learning Technology by providing medical students with more extensive training through the Transparent or Opaque VAM and then testing their ability to respond to "rigged" machine faults on an anesthesia machine connected to a Human Patient Simulator. We expect that the superior understanding of system function that the transparent VAM will provide will lay the foundation for superior operator performance.

Transparent simulations may be both feasible and beneficial in a wide range of medical and health care domains. The challenges to the instructional designer and medical educator are (*a*) to identify "black box" domains where the functioning of a complex system is not explicitly apparent in "physically realistic" depictions; (*b*) where a more accurate understanding of that underlying function of a mechanical, physical or physiological system would enhance clinician performance, on the one hand; and (*c*) be able to specify the most effective "level of abstractness" where the amount of detail can support, and not detract, from that understanding.

When asked which simulation on which they would prefer to continue training, nearly half of the students thought that there would be advantages to being able to use and explore both the Transparent and Opaque simulations. We believe that an ideal sequence may be an initial "grounding" in the physical appearance of the machine with the opaque version, extensive practice with the transparent version, then a final opportunity to work with the physically realistic opaque version to facilitate transfer to the actual machine.

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REFERENCES

1. Hekker JJ. *Computer Animated Graphics as a Teaching Tool for the Anesthesia Machine Simulator.* The Netherlands: Techische Universiteit Eindhoven; 1988.
2. Goldman JM, Ward DR, Daniel L. BreathSim, a mathematical model-based simulation of the anesthesia breathing circuit. *Biomed Sci Instrum* 1996;32:293–298.
3. Sheplock GJ. *Explore! The Anesthesia System.* Madison, WI: Ohmeda Education Services; 1996.
4. Lampotang S, Dobbins W, Good ML, et al. Interactive, web-based, educational simulation of an anesthesia machine [abstract]. *J Clin Monit Comput* 2000;16:56–57.
5. Lampotang S, Lizdas DE, Gravenstein N, et al. Transparent reality, a simulation based on interactive dynamic graphical models emphasizing visualization. *Educ Technol* 2006;46:55–59.
6. Chi MTH, Glaser R, Farr MJ. *The Nature of Expertise.* Hillsdale, NJ: Lawrence Erlbaum; 1988.
7. Lampotang S, Lizdas DE, Liem EB, et al. The Anesthesia Patient Safety Foundation Anesthesia Machine Workbook. University of Florida Department of Anesthesiology Virtual Anesthesia Machine. Available at http://vam.anest.ufl.edu/members/workbook/apsf-workbook-english.html. Accessed October 29, 2007.

8. Bransford JD, Brown AL, Cocking RR. *How People Learn: Brain, Mind, Experience, and School*. Washington, DC: National Academy Press; 1999.

9. Brainerd CJ. Fuzzy-Trace theory: memory. Human learning and memory: advances in theory and application. In: Izawa C, Ohta N, eds. *Proceedings of the 4th Tsukuba International Conference on Memory*. Mahwah, NJ: Lawrence Erlbaum; 2005:219–238.

10. Caplan RA, Vistica MF, Posner KL, et al. Adverse anesthetic outcomes arising from gas delivery equipment: a closed claims analysis. *Anesthesiology* 1997;87:741–748.

11. Gentner D, Stevens A. *Mental Models*. Hillsdale, NJ: Lawrence Erlbaum; 1983.

12. Moray N. Intelligent aids, mental models, and the theory of machines. *Int J Man Mach Stud* 1987;27:619–629.

13. Williams M, Hollan J, Stevens A. An overview of STEAMER: an advanced computer-assisted instruction system for propulsion engineering. *Behav Res Meth Instr* 1981;13:85–90.

14. Halff HM, Hollan JD, Hutchins EL. Cognitive science and military training. *Am Psychol* 1986;41:1131–1139.

15. Butcher KR. Learning from text with diagrams: promoting mental model development and inference generation. *J Educ Psychol* 2006;98: 182–197.

16. Goldstone RL, Son JY. The transfer of scientific principles using concrete and idealized simulations. *J Learn Sci* 2005;14:69–110.

17. Gordon JA, Oriol NE, Cooper JB. Bringing good teaching cases "To Life": a simulator-based medical education service. *Acad Med* 2004;79: 23–27.

18. Hegarty M, Carpenter PA, Just MA. Diagrams in the comprehension of scientific texts. In: Barr R, Kamil ML, Mosenthal PB, et al, eds. *Handbook of Reading Research.* Vol. 2. Hillsdale, NJ: Lawrence Erlbaum; 1991:641–668.

19. Petre M, Green TR. Learning to read graphics: some evidence that "seeing" an information display is an acquired skill. *J Visual Lang Comput* 1993;4:55–70.

20. Schwartz DL. Reasoning about the referent of a picture versus reasoning about the picture as the referent: an effect of visual realism. *Mem Cognit* 1995;23:709–722.

21. Meyers LW, Gamst G, Guarino AJ. *Applied Multivariate Research: Design and Interpretation.* Thousand Oaks, CA: Sage; 2005.

22. Levine TR, Hullett CR. Eta squared, partial eta squared, and misreporting of effect size in communication research. *Hum Commun Res* 2002;28:612–625.

APPENDIX

A multivariate analysis of variance (MANOVA) is used to determine whether there are significant main effects of, or interactions among, independent variables across 2 or more dependent measures. MANOVA avoids increases in "family-wide" risk of a Type 1 (alpha) error (of incorrectly rejecting the null hypothesis), that can occur as the number of comparisons increases, by calculating the F-ratio differently than in the univariate ANOVA. There are 4 approaches to this F-approximation: Pillai's Trace, Wilk's Lambda, Hotelling's Trace, and Roy's Largest Root. We chose Hotelling's T because it is commonly used when there are only 2 levels of the independent variables (see Meyers et al,[21] Chapter 14).

Hotelling's T thus provides an estimate of the probability that an effect is real and replicable. The *strength* of the effect—how strong is the relation between the factor and the dependent measure—is commonly estimated by the η^2 statistic. Also known as the correlation ratio, or R^2, this value reflects the proportion of total variability that is attributable to the effect. It is expressed as the ratio of the effect sums of squares, to the total sums of squares. In multifactor designs, such as the present study, the *partial* η^2 statistic indicates the proportion of total *residual* variability attributable to the effect, after removal of variability for all other effects. Levine and Hullett[22] discuss the use and misuse of the 2 measures of effect strength.