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Knowledge-Driven Design of Virtual Patient Simulations

by Victor Vergara, Thomas Caudell, Timothy Goldsmith, Panaiotis, and Dale Alverson

Two methods are traditionally used in medical education to enhance the realism of learning with simulated scenarios. In these methods, students interact either with human actors trained to mimic the symptoms of a disease or injury or with computer-controlled mannequins that mechanically mimic such symptoms. In scenarios involving either kind of "patient," students apply classroom knowledge while engaging in [experiential learning](#) (Kolb and Kolb 2005). Although such simulated scenarios offer many advantages over strict textbook learning, their use must be limited due to the expense and difficulty of mimicking a wide variety of ailments and situations with either kind of simulated patient. Multiuser virtual environments (MUVES) represent a potential solution to these limitations as they allow instructors to replace physical patients with virtual ones. Like computer-based flight simulators, virtual patient simulators can provide a variety of scenarios that can be repeated as often as necessary to reinforce medical concepts and procedures. In this article, we discuss the design and evaluation of virtual patient simulations in the context of the Mr. Toma Medical Simulation, which has been the subject of multiple studies to assess its effectiveness and usability.

Mr. Toma Medical Simulation

The Mr. Toma Medical Simulation ([Exhibit 1](#)) is a MUVES-based virtual patient simulator that has been the subject of several studies (Caudell et al. 2003; Gutierrez et al. 2007; Mowafi et al. 2004; Pierce et al. 2008). These studies used a [problem-based learning](#) case (Eshach and Bitterman 2003) to demonstrate an evolving epidural hematoma in a virtual patient, Mr. Toma, after an automobile accident. The immersive MUVES permits real-time exploration, examination, and manipulation of the three-dimensional patient and other objects in the virtual world. In an effort to enhance the level of immersion through sound, special attention was paid to the creation of the MUVES's virtual sonic environment (Vergara et al. 2006). The simulation engine allows students to determine how the case scenario unfolds through their interactions with the virtual patient and vary the speed at which events progress within the simulation; users can speed up or slow down the progress of the simulation or return to an earlier point in the simulation to correct errors or replay events.

Students can experience the virtual world in two modes: fully immersed or partially immersed. Fully immersed students wear a head-mounted display with position trackers, which impart a sense of presence and allow users to interact with the virtual environment ([Exhibit 2](#)). Fully immersed users see each other as human avatars within the virtual environment and interact as though they are physically present with each other within the virtual world. Partially immersed users watch the scenario unfold on a computer monitor and use a mouse and joystick to control movements, similar to set-ups for standard gaming systems. Either fully or partially immersed users can work individually or in groups to gather information and initiate interventions. The cost of providing a fully immersed experience for students is approximately ten times that of the partial immersion system, which could represent a significant limitation to the use of fully immersed systems.

Knowledge-Based Design

The development team for Mr. Toma used a knowledge-based design approach (Alverson et al. 2006) to guide development of the virtual patient scenarios in the Mr. Toma simulator and ensure that scenario content and patient behavior were relevant to the course of study. Knowledge-based design begins with the construction of a [knowledge structure](#) to map the important concepts for the domain being taught and determine the teaching goals for the simulation. We employed an interdisciplinary team of subject matter

experts (SMEs) to determine the key concepts crucial to the particular educational domain (Alverson, Caudell, and Goldsmith 2008). Through a consensual process, the SMEs identified, prioritized, and characterized important concepts in each domain and described the semantic interrelationships of those concepts in order to create a knowledge structure that embodied the teaching goals and objectives for the educational domain ([Exhibit 3](#)).

The domain knowledge structure is implemented in the system through an artificial intelligence (AI) engine. The knowledge structure developed by the SMEs forms the basis for the rules that the AI uses to govern the physiology of the virtual patient (Caudell et al. 2003). Those rules are coded for the AI as logical antecedents and consequences; each possible user action produces a particular result within the simulation ([Exhibit 4](#)). The AI determines the behavior of each object inside the MUVE, responding to the user in the manner dictated by the logical structure of the simulation.

Assessing Learning in the Simulation

Although there have been many efforts to teach medical knowledge through virtual training environments, much of this work has lacked formal methods for assessing what students have learned. With Mr. Toma, the development team undertook that work, conducting several studies to determine both the effectiveness and the usability of the simulation in teaching key medical concepts. We hypothesized that students engaged in a virtual training exercise would show the same kinds of changes in their own knowledge structures that are observed when students gain expertise in other learning paradigms, such as practice with actual patients or work with medical histories.

Distributed Use of the Mr. Toma MUVE as a Medical Training Tool

The team of researchers and developers that built Mr. Toma compared the effectiveness and usability of MUVE-based and paper-based learning methods as well as the value of in-person versus geographically distributed collaboration, both within the context of the MUVE and in a paper-based case (Alverson et al. 2005). Fifteen pairs of students, half from the University of Hawaii and half from the University of New Mexico, were divided into four groups, each of whom completed the Mr. Toma case with a different combination of MUVE vs. paper-based administration and distributed vs. in-person collaboration; each group consisted of four teams of two students, except the distributed and MUVE group, which had three teams. Teams collaborated in problem solving and patient management. The in-person, paper-based group proceeded with the exercise on paper; all participants in this group were from the same university and worked in the same room. The distributed, paper-based team used the same documents as the in-person, paper-based group, but one student on each team was located at the University of Hawaii and the other was at the University of New Mexico; the teams communicated using teleconferencing equipment. The in-person MUVE teams were immersed in the Mr. Toma simulation at the same physical location. The distributed MUVE teams also used Mr. Toma, but teams were made up of one student in New Mexico and one in Hawaii.

A test covering the medical concepts invoked by the case was administered before and after the experiment. Changes in students' knowledge were assessed by the before-and-after test score differences. The results ([Table 1](#)) showed that the use of the virtual simulation of the case improved the knowledge of the students as much as the paper-based problem, thus verifying the effectiveness of the MUVE as an alternative to traditional methods. Distant collaboration provided similar performance gains as in-person collaboration for both MUVE users and paper-based participants.

Feedback collected from the participants in a post-experience survey validated the usefulness of the MUVE simulation; indeed, participants who used the MUVE were able to identify several benefits of the environment, including:

- a better understanding of the concepts in the case, resulting from collaboration;
- an increased feeling of engagement over that experienced with text-based cases; and
- increased learning resulting from the ability to repeat actions and correct mistakes by reversing the scenario.

Students also appreciated the opportunity to work with geographically dispersed colleagues with whom they otherwise would not been able to collaborate. Participants were able to share knowledge and experiences between different institutions, enabling them to identify common denominators and unique perspectives as well as determine learning issues for further study.

The Effect of Varied Degrees of Immersion

Another study on Mr. Toma replaced the multiple-choice questionnaire with an assessment process that focused on the development of knowledge structures ([Exhibit 5](#)) to compare the effectiveness of a fully immersive environment with that of a partially immersive environment (Gutierrez et al. 2007). Such a comparison is important because partial immersion requires less equipment and is far less expensive than full immersion.

In this study, participants consisted of 25 volunteers from the first-year medical school class at the University of New Mexico who were taking their neuroscience courses. These students were randomly divided into two groups: a fully immersed cohort in which participants wore a stereoscopic head-mounted display and a partially immersed cohort in which participants interacted with the MUVE simulation via a computer monitor ([Exhibit 6](#)). Both groups used a joystick for navigation, locomotion, and manipulation of objects within the MUVE. Each group studied the same problem-based case.

Knowledge structures were elicited by asking each student to rate the relatedness of 72 pairs of key concepts to each other ([Exhibit 7](#)). SMEs had previously defined 36 pairs of concepts as related and 36 as unrelated to each other. A knowledge structure was elicited from each student before and after the exposure to the simulation. An expert knowledge structure was also created using the same kind of elicitation procedure with the SMEs. Using the [Pathfinder](#) scaling algorithm (Johnson, Goldsmith, and Teague 1994; Schvaneveldt 1990), we compared student knowledge structures with expert knowledge structures. A quantitative index ranging between 0 and 1, with 0 being completely dissimilar and 1 being identical, provided a measure of the degree of similarity between each student's knowledge structure and the knowledge structure created by the SMEs.

A 2x2 repeated measures analysis of variance was performed with pre- vs. post-simulation experience as a within-subjects variable and fully vs. partially immersed as a between-subjects variable. Matched pairs t-tests were then performed comparing pre- and post-simulation scores for the two groups separately. The difference for the fully immersed group was highly significant ($t(12)=5.115, p<0.001$), and the difference for the partially immersed group was also significant ($t(11)=2.625, p=0.024$).

The results showed that both groups benefited from the MUVE simulation training as measured by the significant increase in the similarity between student knowledge structures and the expert knowledge structure after the training experience. The immersed group showed a significantly higher gain than the partially immersed group. While these gains may be significant enough to warrant investment in a full-immersion system if funds are available, a partial-immersion MUVE installation may provide an adequately high learning outcome for those institutions working on a smaller budget. Fortunately, new technological advances and the growing popularity of interactive game systems are substantially reducing the cost for full-immersion devices, rendering them affordable for a wider range of institutions.

Usability Measurements

Usability is also a factor in considering the value of any learning tool, including a MUVE-based patient simulation system as learner perceptions of usability are key to fostering acceptance of the tool. ISO standard 9241 (ISO 9241) defines usability as consisting of three components: effectiveness, efficiency, and user satisfaction. Effectiveness refers to the accuracy and completeness of achieved goals, efficiency is defined by the ratio between the resources expended and the achievements gained, and satisfaction reflects users' attitudes (positive or negative) toward the product. For an educational tool, usability may be measured by the ease with which users can employ the system to achieve a significant degree of learning.

The Mr. Toma team conducted a usability study using the same subject pool described in the previous study (Pierce et al. 2008). The simulation's effectiveness can be seen in the significant learning gains measured in that study, which must be measured against the cost of the equipment required to access the MUVE. The efficiency and satisfaction elements were measured using a questionnaire provided to the students after their MUVE training session (Exhibit 8). The questionnaire consisted of 42 items. The first six asked about participants' experience with virtual reality, video gaming, computers, and the Internet as well as medical experience; these were designed to assess students' relative familiarity with the medium and its content. The remaining 36 questions related to usability. Students rated each item using a four-point Likert scale. The responses of the two groups (fully immersed and partially immersed) were compared using Wilcoxon rank sum tests. Statistically significant differences were based on p values < 0.05 .

There were no significant differences between groups in responses to the first six questions, indicating that participants had similar experiences with related technologies and similar levels of medical experience. Thirty-one of the remaining questions were related to efficiency. Again, there were no statistically significant differences between the two groups. The efficiency scores of the fully immersed subjects using a head-mounted display averaged to 107.4 ± 10.1 (SD); for partially immersed subjects, the scores averaged to 105.7 ± 12.0 , $p = 0.85$. Another four questions measured user satisfaction. Here too, there were no overall differences between fully immersed (14.0) and partially immersed users (13.3), $p = 0.57$. One question related to the number of times the student asked for help. The number of requests for assistance was low in each group (falling within the range of 0-5) with members of the fully immersed group asking for help on average 1.62 times and the partially immersed group, 1.5 times.

In summary, fully immersed students showed statistically greater improvement in knowledge structures than those who were partially immersed. However, there were no significant differences between these two groups in terms of perceived efficiency (ease of use) or satisfaction. Since there were no important differences in efficiency or user satisfaction between the full and partial immersion modes, the only significant distinctions are cost and learning effectiveness. Subjects who were fully immersed scored twice as high on the knowledge structure evaluation as those who were not, but the equipment expense is many times higher, making full-immersion systems less accessible.

Conclusion

MUVE-based virtual patient simulations can help medical students bridge the gap between classroom work and clinical practice. The Mr. Toma simulation described here effectively replaces physical experience with virtual experience as demonstrated by the results of several studies conducted by the research and development team. The simulation employs a knowledge-based design and evaluation methodology that ensures target concepts are properly represented in the simulations and allows instructors to assess systematically whether these concepts are effectively acquired by learners through the simulation experience. We expect that our methodology, which provides a framework within which learning can be identified and measured, may be well suited to other e-learning projects in a variety of fields.

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