Two Novel Technologies for Accessible Math and Science Education

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Two approaches to teaching math and science to deaf and hearing children use 3D animated interactive software.

Sensory-disabled individuals face barriers in schools, workplaces, and social venues. Education related to STEM topics is a pressing problem for the deaf, as deaf individuals are significantly under-represented in science and engineering, and have had difficulty gaining entry to higher-education programs that lead to science, technology, engineering, and, math (STEM) careers. Factors that contribute to this issue include significant delay in development of literacy, difficulty in conveying in sign language basic science and mathematical concepts, and inaccessibility to incidental learning (exposure to media in which mathematical concepts are practiced and reinforced). The challenge facing deaf children is not so much the acquisition of fluent speech skills, but the acquisition of language skills that underlie successful use of speech, signing, reading, writing, and solving even the simplest word problems in math. Significantly, there is a strong correlation between American Sign Language (ASL) fluency and English literacy. English literacy improves as ASL skills improve and knowledge of ASL as a first language is beneficial because it taps normal capacities at appropriate developmental stages.

This article presents two 3D animation-based approaches to education for the deaf and reports the findings of our evaluation. Both approaches are unique because they use advanced technology to teach mathematics to K–4 deaf students who know ASL; provide equal access and opportunities by overcoming known deficiencies in STEM; and provide a teaching model that can contribute to improving deaf education in general. The evaluation results show that deaf children generally took longer to accomplish various tasks in comparison to hearing children, and that girls generally took longer than boys. Nonetheless, all children were able to engage with and complete the tasks in both approaches.

3D computer animation and sign language

Computer generated and controlled animation has unique advantages over other media, such as photo and video clips, including

- user control of appearance (for example, point of view control and zoom);
- image quality, such as no distracting details of the sort found in photos and films;
- user control of texture and transparency;
- user control of the motion speed;
- user programmability for generating infinite number of drills, unlimited text encoding, real-time translation, and limitless combinations of signs;
- inexpensive new content development (once authoring tools have been created);
- smooth combination of signs into words and sentences without abrupt jumps or collisions between successive signs;
- low bandwidth because the programs controlling animations can be stored and transmitted using only a small percent of the bandwidth required for comparable video representations; and
- character control, letting signs animated on one character to be easily applied to other characters.

Vcom3D’s SigningAvatar (see http://www.vcom3d.com/) offers several of these advan-
tages and represents the state of the art in computerized animation applied to sign language. SigningAvatar software uses computer-animated 3D characters who communicate in sign language and use facial expressions. The fundamental value of this pioneering technology lies in the fact that by using computerized animation, it provides a low-cost, interactive means for adding sign language to media.

As another example of the benefits of 3D technology over traditional media, the ViSiCAST project provided deaf citizens with improved access to services and facilities through animated sign language. Its specific objective was the realization of a natural text-to-sign-language animated translation through the use of avatar technology. The project is now being continued by eSIGN (see http://www.visicast.cmp.uea.ac.uk/eSIGN/index.html). To date, eSIGN has produced software tools that allow Web site and other software developers to augment their applications with signed versions.

Although our work follows in the trail pioneered by Vcom3D and ViSiCAST, with the Mathsigner 3D animation ASL-based interactive software package we have significantly improved on the current state of the art in terms of appearance of the signers and quality of the signing motion. We believe these improvements translate into a significant impact on deaf children’s willingness to engage with the 3D avatars, and therefore learn.

VR technology in deaf education

Although the benefits of VR experiences need to be more comprehensively defined, studies show that VR can provide a more effective learning tool than traditional classrooms and that students enjoy working with virtual worlds. Research also shows that VR is particularly suitable to math and science education because of its ability to bridge the gap between the concrete world of nature and the abstract world of concepts and models, making it a valuable alternative to conventional study that requires students to develop understandings based on textual descriptions and 2D representations.

In regard to education for those with disabilities, VR has advantages over other teaching technologies because it can provide for the learning requirements of students. Some of the most commonly encountered needs include

- access to safe and barrier-free scenarios for daily living tasks;
- self-pacing;
- repetition;
- control over environment;
- ability to see or feel items and processes in concrete terms; and
- motivation.

To date, only two examples of virtual environments for deaf and speech-impaired students exist: the Virtual Supermarket developed at the University of Nottingham, England, and the Virtual Reality Education for Assisted Living (VREAL) project, funded by the US Department of Education.

Our approach, Science and Math in an Immersive Learning Environment (Smile), builds on projects such as VREAL. Smile is the first bilingual immersive virtual learning environment featuring interactive 3D animated characters that respond to the user’s input in written and spoken English as well as ASL. Smile provides an ideal combination of technological innovation and educational content by presenting an emotionally appealing and age-appropriate visual design; an engaging game strategy that establishes a meaningful context for participation; and goal-oriented activities grounded in research on effective pedagogy, addressing Roussou and Barab’s argument that high-end technological innovations are often associated with disappointing content.

We designed Smile for formal science and math education and we will make it available for use by elementary schools and deaf education programs throughout the US. Smile can be displayed on several immersive, non-immersive, stationary, and portable platforms, including low-cost immersive fish-tank systems. To date, immersive virtual learning environments have not made their way into the classrooms primarily because they require high-end display systems that schools can’t afford. Smile solves this problem.
Smile

Smile is an immersive learning game that employs a fantasy 3D virtual environment and a bilingual interface (English and ASL) to engage deaf and hearing students in math- and science-based educational activities. Students can explore the town of Smileville, enter buildings, select and manipulate objects, construct new objects, and interact with the characters. Smile has an overall story with an overarching goal (restore the lost willingness to smile in the city of Smileville), which creates a boundary condition uniting all the individual game tasks. Each activity takes the form of a good deed whose objective is to make a Smileville character smile again by giving him or her a meaningful new object. The ability to construct the object is dependent on the acquisition of STEM skills and related ASL signs. Key design features of the game include basic geometric shapes with round edges, vibrant and varied colors, and a bright lighting setup with limited shading and soft shadows. Figure 1 shows examples of Smile’s visual style; Figure 2 shows examples of Smile virtual signers.

Smile can be displayed on different systems: stationary, four-wall projection devices (the Fakespace Flex, see http://www.fakespace.com/flexReflex.htm), fish-tank VR systems, and standard desktop computers. Figure 3 shows Smile on two displays. Additionally, we can modify the application to view it through a head-mounted display. Portable demos of Smile are available for download at http://www2.tech.purdue.edu/cgi/i3/smile/. A detailed description of Smile can be found elsewhere.12

Mathsigner

Mathsigner, our second approach, is a 3D-animation, ASL-based interactive software package that contains sets of activities, with implementation guidelines, to teach K–4 math concepts, signs, and corresponding English terminology to deaf children, their parents, and teachers.

In developing Mathsigner, we used a state-of-the-art optical motion capture system to record the signs directly from a fluent signer. Six cameras captured each sign individually and applied it to the 3D characters in real time for immediate feedback and editing on readability and realism. We accomplished smooth transitions between individual signs via an algorithm that we developed.13 The algorithm allowed for real-time blending of individual animation segments and yielded smooth signed sentences from sequences of single signs. In other 3D signing programs, the transitions between signs are implemented with cut-and-paste methods or simple linear interpolation; the result is unrealistic movements. A detailed description of the blending technique can be found elsewhere.14

We modeled the 3D signers (realistic and fantasy) as seamless polygonal models and rigged them with state-of-the-art deformation techniques that allow for natural skin deformations during motion. The majority of existing signing avatars are segmented characters made of rigid components, and don’t deform as they move.

Adamo-Villani and Beni developed a parameterized graphical facial model with a set of 26 parameters, each controlled by a letter on the keyboard.15 The method allowed for real-time encoding of facial expressions with accuracy and realism. Such facial modeling represents improvement over existing avatars whose facial expressions are mechanical and limited to a small set.

We have a fully functional prototype that teaches grades K–3 math concepts and related ASL signs. We based the math content on standard, published elementary school math
curriculum and developed the content with feedback from the teachers at the Indiana School for the Deaf. Mathsigner is not just for animated signing, but is an integrated package with math activities sorted by grade level concepts and difficulties. We designed the software to be delivered via the Web or CD-ROM, with no special system requirements or further programming required. No other interactive, 3D-animation-based software exists for math education of the deaf.

The current prototype contains two programs, one designed for deaf children and the other for hearing parents. Each has two modes of operation: a learning mode and a drill mode. The screen layout consists of two frames: the frame on the left lets users select the grade (K, 1, 2, or 3) or the type of activity; the frame on the right shows the 3D signer. Figure 4 shows two screen shots from Mathsigner. A demo of the prototype learning tool is available at http://www2.tech.purdue.edu/cgt/I3/.

Formative evaluation

We used a formative evaluation to collect data and information to improve our systems. A typical formative evaluation involves one-on-one, small-group, or field-trial evaluations conducted directly with learners. We conducted a pilot study in the spring of 2007 involving 21 participants. The group included 7 deaf and 14 hearing children ages 6 1/2 to 10. The group consisted of 13 males and 8 females. Our goal for the study was to assess the fun and usability of Mathsigner and Smile. All 21 subjects participated in the Smile evaluation; the 7 deaf subjects participated in the Mathsigner evaluation.

A game’s usability and how fun it is are closely related. According to the ISO 9241-11 definition, usability is derived from three independent measures: efficiency, effectiveness, and user satisfaction. Even if systems designed for children don’t neatly fall into this definition, some researchers have postulated that fun is one manifestation of what adults call satisfaction. We believe that fun is much more than a child’s expression of satisfaction. We based our evaluation of fun on the three dimensions of fun proposed by Read, Macfarlane, and Casey: expectations (that is, the component of fun that derives from the difference between the predicted and reported experience), engagement, and endurability (that is, the desire to do an activity again because it is enjoyable). Our evaluation methodology to measure fun included: ranking and rating exercises, observation, and thinking aloud. Meanwhile, the usability evaluation included four common techniques: user task scenario development, key usability factor measurements (learning time, completion time, number of errors, and completion or noncompletion related to tasks), thinking aloud, and observation.

Because we focused this evaluation exclusively on fun and usability—not on learning and knowledge acquisition—we gave all participants a pretest before they began the interactive session. The objective of the pretest was to ensure that all subjects had the basic mathematics skills necessary to complete the activities. The pretest included questions relative to the participant’s expectations of the game and questions pertaining to familiarity with computer games.

Smile usability evaluation

Many activities in Smile require the participant to travel to different areas of the town and enter and explore buildings. Bowman et al. have identified three types of travel tasks in virtual environments: exploration, search, and maneuvering. Our study focused on first-person travel for primed search—in a primed search, users know the target’s location a priori.
Object interaction in virtual environments includes object selection and manipulation. Object selection is defined as “the user acquiring control of an object or group of objects.” Once an object is acquired, any operation performed on the object, such as relocating, reorienting, querying, and modifying, is considered object manipulation. Our study focused on object selection, reorientation, and relocation.

The goal of our study was to evaluate and compare the usability of two interfaces (wand and pinch glove) and determine the most effective one for the application’s target users (that is, children ages 6 1/2 through 11). For evaluating Smile, we selected the quality factors of learning time and speed of completion as the key attributes to indicate the effectiveness of immersive interfaces.

Interfaces

We built both user interfaces using commercially available hardware components; they are both suited for travel and object interaction in several virtual environments.

The wand interface uses a 6-degrees-of-freedom InterSense I-900 wand. The wand has six buttons and a pressure-sensitive joystick that can be programmed. In Smile, users employ the joystick for moving through the environment: wand orientation specifies direction of travel, and velocity is proportional to the displacement of the joystick from its origin. Users rotate by depressing the green button and moving the wand in the desired direction. Users grasp and release objects by pressing and releasing the trigger on the back of the wand.

We made our pinch glove interface using a pair of Fakespace pinch gloves and an InterSense IS-900 wrist tracker. In Smile, users can grasp and release objects within reach by pinching the thumb and forefinger together; input the ASL numbers 0 through 9; and travel through the environment. To move, users touch the palm with the pinky, ring, and middle fingertips and point in a direction; to rotate the environment users pinch their ring finger and thumb together and rotate their arm. The main advantage of this interface is that it eliminates the need for a hand-held navigation device and allows for the use of both hands to interact with virtual objects in a natural and intuitive way.

In Smile, users input ASL number hand shapes and grasp and release gestures with the dominant hand and navigation gestures with the nondominant hand. Our decision to assign signing and object manipulation tasks to the dominant hand and navigation tasks to the nondominant hand was based on research in human motor behavior. Findings show that the nondominant hand is generally preferred for large-scale positioning, while the dominant hand is preferred for fine-grained tasks. Moreover, humans tend to position their dominant hand relative to the coordinate system specified by the nondominant hand.

Experiment design

The two experiments took place in the Flex VR Theater at the Envision Center for Data Perceptualization at Purdue University.

To assess travel functions, we assigned subjects the task of traveling from a start point (the Smileville sign) directly to the door of the bakery building, which is visible from the start point. The bakery door is shown in Figure 5a. When a subject reaches the target, the door knob blinks. We tasked the children with reaching the target location with both the pinch glove and the wand interface. We employed a terrain-following constraint to limit the subjects to a specific plane. In other words, subjects had to walk instead of being able to fly freely to the bakery.

To assess users’ ability to interact with objects, we assigned subjects the task of making a cake by following a given recipe. The activity started with the subjects in the center of the baking room and involved a series of object selection and manipulation tasks. In particular, we asked the children to read a recipe (displayed on the wall), select the correct ingredients located on the baking room counter, place the ingredients on the...
scale, put the correct amount of ingredients in a cake pan, open the oven door, put the cake pan in the oven, and open the oven door to see the result when the timer beeped. Figure 5b shows the baking room.

We administered both tests (travel and cake baking) as crossover design experiments, with 10 subjects using the pinch gloves first, and the other 11 using the wand interface first. We randomized the sequencing of the two activities among interfaces and subjects, and recorded and analyzed the subjects’ time required to learn how to use the interfaces, to reach the target location, and to complete the cake baking activity. In addition, we asked subjects to identify the interface that they perceived as the most fun.

Results

The mean wand learning time was 90.6 seconds (27.9 second standard deviation) and the mean glove learning time was 88.3 seconds (19.6 seconds). This difference was not significant. Neither age nor video familiarity were significant correlates. Gender did not have a significant effect. Learning time did differ significantly by hearing status: $F(1, 15) = 15.1, p = 0$, with deaf children (97.1 seconds) taking 16 percent longer than hearing children (83.9 seconds). Note, “$F$” and “$p$” are statistics associated with analysis of variance. The $F$-test or $F$-ratio is a test of the overall null hypothesis that there is no difference between group means on dependent variables. The numbers in parentheses are the degrees of freedom ($n - 1$) on which it is calculated. The $F$ statistic 15.1 is the ratio of between-group (wand versus glove) mean square variance divided by within-group (all the learning times) mean square variance. $p$ is the significance level expressed as probability; typically a value below 0.05 is taken to indicate that the effect (in this case difference in learning time) is real and not an accident of sampling or chance; the smaller the $p$ value, the greater the degree of confidence in this finding.

The mean wand travel time was 80.86 seconds (24.4 seconds) and the mean glove travel time was 78.33 seconds (17.7 seconds). The difference approached significance: $F(1, 15) = 3.95, p = 0.065$. Neither age nor video familiarity were significant correlates.

Travel time differed significantly by hearing status: $F(1, 15) = 41.0, p < 0.0001$. Overall, deaf subjects (mean 94.2 seconds) took 26 percent longer to navigate than hearing subjects (mean 74.6 seconds).

Travel time differed by gender, approaching significance: $F(1, 15) = 4.38, p = 0.054$. There was no hearing status by gender interaction, that is, girls took longer than boys for both deaf and hearing groups. Girls (90.9 seconds) took 17 percent longer to navigate than boys (77.9 seconds), a statistic that future research should consider to determine if gender is actually a factor.

For interaction with objects, the within-subject mean wand activity time was 344.5 seconds (48.8 seconds) and the mean glove activity time was 333.5 seconds (28.8 seconds), which was not significant. Neither age nor video familiarity were significant correlates.

Between-subjects activity time was significantly correlated with video game familiarity: $F(1, 15) = 5.2, p = 0.04$. There was a significant between-subjects effect of hearing status on activity time: $F(1, 15) = 8.7, p = 0.01$. Deaf children’s overall activity times (373.7 seconds) were 13 percent longer than the hearing children’s (331.0 seconds). In addition, there was a significant difference in within-subject activity times by hearing status: $F(1, 15) = 30.5, p < 0.0001$. Deaf children’s activity time for the wand (384.9 seconds) was 16 percent longer than for the glove (331.0 seconds). Hearing children’s activity times with the wand (324.5 seconds) and the glove (334.7 seconds) were close to each other.

There was a significant between-subjects effect of gender on activity time: $F(1, 15) = 10.5, p = 0.005$. Girls took 12 percent longer (372.5 seconds) than boys (332.1 seconds). There was no hearing status by gender interaction.

Within-subject activity times were marginally affected by gender: $F(1, 15) = 4.4, p = 0.054$. Girls’ wand activity times were 7.4 percent longer (374.6 seconds) than their glove activity times (348.9 seconds), whereas boys’ wand (326.0 seconds) and glove (324.0 seconds) activity times did not differ.

To summarize the gender differences, we observed that learning time for boys and girls is the same, girls spend more time doing the activity, girls seem to spend more time navigating between locations, and it is possible that girls have more difficulty using the wand, which needs to be investigated further.
to determine if that is the reason why girls take longer on the activity and on navigating.

**Mathsigner usability evaluation**

The experiment took place at the Envision Center for Data Perceptualization at Purdue University. We gave participants detailed instructions (in ASL and spoken English) and demonstrations on how to interact with the Mathsigner software using mouse and keyboard. We asked them to carry out basic tasks within the program, including performing a sequence of goal-oriented activities that involved navigating to specific sections of the program, entering text, selecting and moving 2D objects, manipulating the view of the 3D avatar, and changing the signing speed. Children worked alone and sat in front of a 21-inch display with a resolution of 800 × 600 pixels.

A researcher recorded the time necessary to complete the sequence of activities by pressing a key at the end of each testing session. This action stopped the timer and the video screen capture that was started automatically upon display of the Mathsigner introduction screen. We analyzed the video screen captures to determine the nature and number of mistakes made by the participants and the possible bugs in the software.

In terms of interaction with objects, activity times for Mathsigner neared significance for a gender effect: $F(1,5) = 5.7, p = 0.06$. Girls took 11 percent longer (265.7 seconds) than boys (239.0 seconds). The number of errors made while interacting with Mathsigner also differed by gender, $F(1,5) = 8.4, p = 0.034$. Girls made nearly three times more errors (5.0) than Boys (1.8). Because no wand or glove is involved with Mathsigner, we cannot attribute use of these tools as the sole reason why girls take longer or made more mistakes. Some other factor(s) must contribute to the difference between boys and girls. The difference in errors made suggests that the girls might have more difficulty with the math itself or with the software program, or both, or that the girls are less comfortable with the task or the content.

**Evaluation of appeal**

After completing the hands-on testing sessions for both Mathsigner and Smile, we asked the subjects to fill out a survey with questions and tables used to measure endurance and expectations; we used observation and the think-aloud protocol to assess engagement. Children rated activities and elements of the game using a scale consisting of smiling and frowning faces. Research shows that children are able to respond more reliably to a pictorial representation with meaningful anchors (smiling and sad faces) rather than to a Likert-type scale.18 We recorded all hands-on testing sessions on video and scored the footage with reference to a set of positive and negative instantiations.

**Expectations**

For the girls, Smile was more fun, easier to play and use, and offered more challenging activities than they expected. For the boys, it was more fun and the activities were more challenging and not as easy to play as they expected. For the girls, Mathsigner was more fun, easy, and challenging than they expected. For the boys, it was more challenging than they expected, but as much fun and as easy as they expected.

**Returnance**

All boys and girls were eager to return and play the entire Smile game again. Activities that all children wanted to repeat the most were watching the beginning animation and traveling through town.

For Mathsigner, girls most wanted to return to learning to count and learning shapes. They least wanted to return to testing multiplication and division and learning the clock. Boys most wanted to return to testing shapes and learning the clock. They least wanted to return to testing addition and subtraction and testing multiplication and division.

**Engagement**

Regarding Smile, observation and think-aloud protocol showed that activities the participants found engaging were walking through objects, throwing objects around, opening doors, and watching things that move. The majority of the subjects appeared very focused on the tasks. Positive comments included “this is awesome because you feel like you are really in a bakery” and “…this game is more exciting than a video game because you don’t see anything around you…. “ During the experiment, participants displayed many positive signs, such as laughing, smiling, bouncing in excitement, and
saying “wow.” We noticed a few signs of frustration and comments, such as “some of the ingredients are really hard to pick up,” “the scale is hard to read,” and “the 3D glasses really bother me.”

For Mathsigner, all participants appeared engaged with the activities. Comments included “this is really cool,” “this game makes math easy,” “the activities are difficult,” and “I like the Bunny signer.”

Smile was rated most fun of the two. Descriptive statistics (for example, tables and diagrams) for all tests are available at http://www2.tech.purdue.edu/cgi/i3/smile/AdamoWilbur.htm

**Discussion and conclusion**

We are using the results of the study to improve the design of both programs. We plan to repeat these evaluations several times as development of both programs progresses. Evaluation with kindergarten and elementary school deaf children and their teachers will be done in collaboration with the Indiana School for the Deaf and will start in the fall of 2009. We will report the results in a future article.

A strong need exists for solutions that allow deaf users to communicate and interact in an environment free of prejudice, stigma, technological barrier, or other obstacles. The fact that all children were able to engage with and complete the tasks in both test systems is encouraging.

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**References**


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