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A Virtual Learning Environment for Deaf Children: Design and Evaluation

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Abstract**—**The object of this research is the design and evaluation of an immersive Virtual Learning Environment (VLE) for deaf children. Recently we have developed a prototype immersive VR game to teach sign language mathematics to deaf students age K-4 [1] [2]. In this paper we describe a significant extension of the prototype application. The extension includes: (1) user-centered design and implementation of two additional interactive environments (a clock store and a bakery), and (2) user-centered evaluation including development of user tasks, expert panel-based evaluation, and formative evaluation. This paper is one of the few to focus on the importance of user-centered, iterative design in VR application development, and to describe a structured evaluation method.

Keywords**—**3D Animation, Virtual Reality, Virtual Learning Environments, User-Centered Design, User-centered Evaluation.

I. Introduction

RECENTLY we have created a prototype immersive virtual learning environment in which deaf children (age 5-10) interact with fantasy 3D signers and learn American Sign Language (ASL) math terminology and concepts [1] [2]. The application can be displayed in stationary VR projection systems (such as the FLEX [3]), and can be interacted with using a pair of pinch gloves, or a 6 degrees-of-freedom (dof) wand, coupled with a wrist tracker.

The virtual world includes a series of stores in which the participants perform hands-on, minds-on math activities based on standard elementary school curriculum. Users have the ability to explore the stores, select and manipulate objects, and communicate with the virtual store keepers in American Sign Language.

In this paper we describe the user-centered, iterative design approach, and user-centered evaluation methodology currently being used to transform the prototype into an effective working application.

In section 2 we give an overview of current research in design and evaluation of Virtual Environments (VEs). In section 3 we describe the design of the visual representation, interaction methods, and interactive content, and we give a brief explanation of how the application is implemented.

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In section 4 we describe the evaluation methods and we report the results. Discussion of results and recommendations for future iterations of the VE are presented in section 5. Conclusive remarks are included in section 6.

II. Background

Until recently, research in VE has focused primarily on improving the technology, without much attention to usability, and to the specific needs and preferences of the target users. As a result, many VR applications are non-engaging and difficult to use and, therefore, non-effective for their users [4]. In the past few years, user-centered design and usability engineering have become a growing interest in the VR field. A few researchers have started to recognize the importance of VE design and evaluation, and are keen on developing practical solutions to the problem. For example, Hix et al. [4] [5] have proposed an iterative methodology for user–centered design and evaluation of VE user interaction, while Bowman et al. [6] have presented a methodology for the evaluation of travel methods in immersive VE. Sutcliffe et al. have suggested methods for evaluating the usability of virtual reality user interfaces [7] and Slater has focused on evaluation and measure of presence [8]. In regard to design and evaluation of VE for special-needs education, Neale et al. [9] have described an evaluation framework and analysis method which was used to assess the behavior of the participants, as well as the quality of the design, of VLEs for children with severe learning disabilities.

Despite these research efforts, with the relatively small number of experiments and the fluid nature of VE systems and applications, generalizable results are few and far between [10].

In an effort to contribute to this new and evolving area of research, in this paper we describe the design process and evaluation methods used in the development of a VLE for deaf children. Although the design approach and evaluation techniques presented are specific to our application, they could be generalized and used as guidelines for design and evaluation of similar educational VEs.

III. User-Centered Design and Implementation

All design decisions relative to visual representation, navigation, object manipulation, and interactive content, were based on: (1) knowledge of the target users' physical, emotional, and cognitive needs; (2) research findings on children's preferences of visual style, color, and lighting, and on the impact of color and light on learning; and (3) continuous feedback from the target age group.

A. Visual Representation

The virtual world is represented in a visual style with which the target users of the application (children age 5-10) are familiar: it is cartoon-like. Disney's Toon-town [11] was used as a visual reference for the design of characters and environments. Key design features of the environments include basic geometric shapes with soft and round edges, vibrant and varied colors, and a bright lighting setup with limited shading and without shadows. The choice of the color and lighting schemes was based on research studies on the impact of color and light on learning [12] [13], and on the association between colors and children's emotions [14]. One study shows that de-saturated colors have a negative impact on stimulation while highly saturated colors increase alpha waves in the brain which are directly linked to awareness. Another study reports that younger children (5-years-old to 6 ½-years-old) are especially attracted to vibrant and warm colors and most positive emotional responses are associated with very bright colors. Research on the relationship between light and learning suggests that a bright lighting setup, with the presence of daylight, is associated with improved students' performance [15]. The color palette and lighting scheme of our virtual environments represented in Figs. 1 and 2, show adherence to the above mentioned research findings.

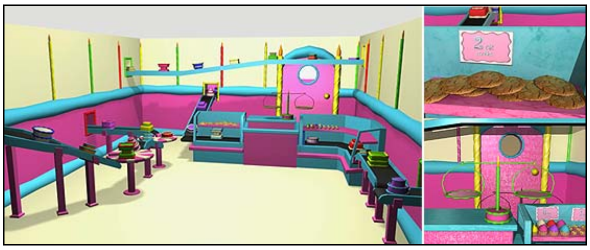
Fig. 1 The virtual Bakery

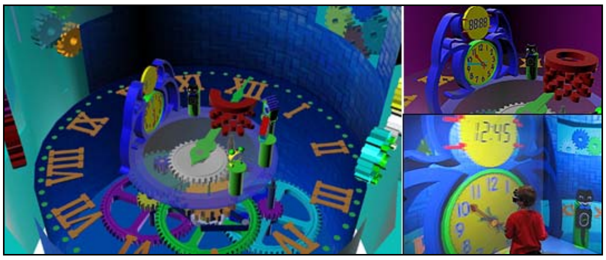
Fig. 2 The virtual clock store

To make object manipulation as intuitive and comfortable as possible for the target users, we considered the average height of US children age 5-10 [16]. As a result, all selectable objects are placed at a height corresponding to the target users' middle chest average distance from the floor.

In regard to character design, the major challenge faced was the need to create low- poly, cartoon like avatars, appealing to young children, but capable of signing in a very realistic manner--since accuracy and readability of the signs is one of the main requirements of the project. After several design iterations with continuous feedback from children age 5-10, we created two avatars, a robot and a pig, with emphasized facial features and large hands to enhance readability of facial expressions and signing gestures. The design of the characters, shown in Figs. 3 and 4, is consistent with the visual style of the environments, and though the avatars are very stylized, they move in a natural and fluid manner, and deform organically during motion. In order to accomplish this, the characters were modeled as continuous polygon meshes with a poly-count that does not exceed 6000 polygons per character. A low polygon count is necessary in order to maintain the high frame rate and real-time interaction needed in the FLEX. To realize high visual quality with a limited number of polygons, we optimized the 3D surfaces by concentrating the polygons in areas where detail is needed the most: the hands and the parts that bend and twist (i.e., elbows, shoulders, wrists, and waist). With such distribution of detail we are able to represent realistic hand configurations and organic deformations of the skin during motion. Each character was set up for animation with a skeletal structure that closely resembles a real human skeleton and the geometry was bound to the skeleton with a smooth skin. The face of each 3D signer was rigged with bone deformers, the only technique supported by Cal 3D [17]. To achieve fluidity and realism of motion, the virtual signers are animated with a library of signing clips recorded directly from an ASL signer wearing a Metamotion 19-markers optical motion capture suit [18] and a pair of Immersion 18-sensors cybergloves [19]. Keyframe animation was used to animate various facial expressions such as eye blinks, eyebrow deformations, and mouth movements; directional constraints were used to control gaze direction.

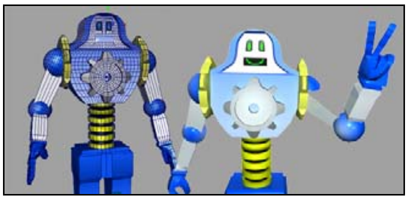
Fig. 3 Clock store character. Polygonal mesh, left; rendered image, right


Fig. 4 Bakery character. Skeletal rig, left; rendered image, right

B. Interaction

Interaction with the application is in the form of a walkthrough with the abilities to select, grasp, move, and release objects, and communicate with the virtual store keepers in sign language.

Navigation. In general, navigation in virtual worlds involves two separate components: travel and way-finding [20]. In the current implementation of the application, the individual environments (stores) are not connected and are loaded in the FLEX one at a time, therefore way-finding is not necessary. Moving through the environment is accomplished by physically walking within the confines of the FLEX. We chose not to use any cumbersome travel interface, and we have temporarily removed the ability to use the wand for 'controlled' walking, in order to provide an intuitive, non-intrusive method of travel, and thus allow the children to focus entirely on the learning experience.

Object manipulation. Many of the objects in the VEs can be selected, picked up, moved, and relocated. After examining different manipulation methods, we selected two forms of object manipulation: direct user control and physical control. The choice was motivated by the fact that these techniques require very limited learning and abstraction from the participant. Direct user control is implemented with a pair of Fakespace pinch gloves [21]; physical control utilizes a 6 dof wand whose buttons provide the means for interaction with the world. We keep the functionality of the buttons consistent throughout the experience in order to minimize the participant's memory load. Both the gloves and the wand are coupled with a wrist tracker which records the position of the user's hand in space. While the pinch gloves allow the participant to interface with the virtual objects in a very natural way, using gestures that mimic real world interaction, they present the problem of different hand fits. The wand, instead, though not as intuitive as the gloves, was found easy to use because it operates like many video game controllers with which kids are familiar.

Users use the most natural and intuitive way to select and pick up an object: they reach out to it and 'touch' it. Each object is the child of a translation node with a 4 x 4 matrix defining its position and orientation in three dimensional space. When an object is grabbed by the wand (or glove), the translation matrix of the object is set equal to the wand's (or glove's) matrix and the object's translation matrix is updated each time the wand (or glove) is moved. When the user lets go of the object (by releasing the wand button or opening the fingers), the object no longer receives data from the wand (or glove); its matrix is sent through a series of functions which apply physics to the translation parameters, thus enabling the object to fall and collide with the floor (or store counter, or scale).

Interactive activities and communication with the virtual signers. Each virtual store has been designed for learning and practice of a specific math concept and related ASL math terminology. For instance, in the bakery, children learn how to estimate, measure, and sign weight; in the clock-store they learn how to read and sign time; in the toy store (currently under development) they become familiar with the concept of money. In every store a virtual store keeper communicates with the participant in sign language. The storekeepers give the user signed feedback upon completion of certain tasks and/or solution of math problems, and ask questions in sign language; each question requires a number as an answer. The user responds by producing the number sign with the pinch glove, or by selecting the number symbol from a virtual menu which appears in front of the user when activated (by pressing a button on the wand). All interactive activities are based on standard published K-4 math curriculum and have been designed with continuous feedback from ISD teachers who are familiar with the preferences and needs of the target users. In addition, ISD teachers have provided feedback on ASL that is appropriate for the target age groups. For example the concept 'multiply' is represented at younger grades with the symbol 'x' and at upper grades with the symbol '*'. Thus the signs need to be properly chosen depending on the grade level of the user. This is done directly by the teachers who use a set up menu to select the correct signs based on the grade and age of the participant, before interaction starts.

C. Application Development

The participant views the application through a pair of light-weight shutter glasses as it is projected onto a stationary four screen VR display (i.e., the FLEX [3]). This display provides the user with images of the virtual environment projected to the front, side, and floor screens. The user wears an InterSense head tracker [22], which enables the application to determine the position and orientation of the user's eyes; this information is used to re-draw the environment based on the user's point of view. The participant interacts with the virtual world using a gesture control system, described in [1] [2], or an Intersense IS 9000 wand and wrist tracker. Interaction with the environment cues animated responses from the virtual objects and characters. Figure 5 shows a target user interacting with the application in the FLEX.

Fig. 5 User in the FLEX

Characters (and environments) were modeled and rigged in Maya 7.0 and 3D Studio Max 8.0 and animated using motion capture technology and keyframe animation. Several software packages and libraries were used to convert the 3D data into a format compatible with the specialized hardware. Graphics are rendered in the FLEX using OpenSceneGraph [23], an open source graphics development toolkit which works on top of OpenGL. Communication between the OpenSceneGraph libraries, the FLEX display system, and the input devices is implemented with the VRJuggler toolkit [24]. OsgCal, an adaptor for the Cal3D character animation library, allows the application to use Cal3D's functions to control skinned character animation within the OpenSceneGraph driven virtual environment. OsgCal functions are used to control playback and real-time blending of the animation clips.

A detailed description of how the application was developed can be found in [1] [2]. Demos of the program are available at:

http://www2.tech.purdue.edu/cgt/I3/SMILE/demos.html

IV. Evaluation

Evaluation of the application takes three different forms, expert panel-based, formative, and summative. The expert panel-based evaluation and the formative evaluation focus on the **design features** of the application and on the quality of the **signing motion**. The summative evaluation tests the **efficacy** of using a computer animated 3D sign language based immersive virtual environment for teaching math concepts to deaf children in grades K-4. In this paper we describe the first iteration of the expert-based and formative evaluations. We plan to repeat these evaluations three times before summative evaluation takes place, with each evaluation session resulting in an improved design iteration. Summative evaluation with kindergarten and elementary school aged deaf children and their teachers will be done in collaboration with the Indiana School for the Deaf (ISD) in Spring 2007; the results will be reported in a future publication.

A. Expert Panel-Based Evaluation

The expert panel evaluation aims to assess: (1) usability of the program; (2) overall quality of the virtual world; and (3) quality of the signing motion. Usability is defined as 'ease of use and usefulness' of the application [6]. Overall quality of the virtual world refers to quality of the visual representation (i.e., quality of 3D graphics, lighting setup, environment layout, animation, and overall appeal to target users). Quality of the signing motion is defined as realism, accuracy, and readability of the individual animated signs and the signed sequences.

The panel consists of six individuals: two experts in VR application development, two experts in 3D modeling and animation, and two experts in American Sign Language. Each expert was asked to perform an analytical evaluation of the elements of the application that pertained to his/her area of expertise. The goal of the analytical evaluation is to identify potential problems and to make recommendations to improve the design. The two experts in VR application development assessed the usability of the program by determining what usability design guidelines it violates and supports. This presented a challenge since clear heuristics for the ideal design of VEs to guide usability evaluation do not exist yet [10]. The set of usability design guidelines used in this study was derived from previous work by [25] [26] [27] [7].

The experts in 3D modeling and animation were given a questionnaire with questions focusing on the quality of the visual representation of the virtual world; the experts in ASL were given a similar questionnaire with questions on the quality of the signing motion. The evaluators used a five point Likert scale for rating the response to each question and used comment boxes to provide additional feedback

1. Results

Overall, the application was found easy to use and all evaluators were able to complete the users' tasks without difficulty. However a few usability problems were identified. The application violates the first of the ten usability heuristics proposed by Nielsen [25]: 'Visibility of System Status'. Currently, the program has two modes of operation, a learning mode and a practice/drill mode and the user can switch between them by pressing a button on the wand, or by making a specific gesture with the pinch glove. However, the system does not provide any feedback on the current mode the participant is in; as a result, the user is confused about which tasks to perform. Another usability guideline currently not supported is 'Supply users with appropriate selection feedback' (from [27]). In the current implementation, participants do not receive any feedback upon selection, thus they are not able to ascertain which, if any, objects are selected until they move them. Other problems identified were lack of help, error feedback, and ability to 'undo' [25] [27]. Presently, children are expected to use the application in the presence of a supervising teacher who gives directions and help; in future iterations the application will include signed help and directions provided directly by the virtual store keepers. As far as navigation, the experts pointed out that way-finding methods, as well as alternative travel techniques, will become necessary once the stores are connected to form a seamless environment.

In addition, the experts in VR application development evaluated system performance, i.e., total latency, display update rate, tracking performance, etc., all aspects were found satisfactory for the goal of the project and its target audience.

All elements of the visual representation as well as overall quality of the signing motion were given high scores by the experts in modeling/animation and ASL. In particular, the signed animation received very positive rating and, therefore, recommendations for improvement were not necessary. Evaluation results are reported in Table I.

TABLE I
EXPERT PANEL EVALUATION RESULTS

Evaluation Questions	Mean Values (1-5)
VISUAL REPRESENTATION	
Overall quality of visual style and appropriateness for target age group	**4.5**
Quality of 3D models (environments and characters)	**4.5**
Quality of composition and environment layout	**5**
Quality of materials, textures, color design, and light design	**4.5**
Quality of non-signing animation (motion and timing)	**4**
SIGNING MOTION	
Overall realism of signing motion	**5**
Overall readability of signs	**4.5**
Fluidity of transitions between signs	**4.5**
Placement of signs in relation to body	**5**
Accuracy of signs	**5**
Quality of non manual signals (facial expressions)	**4.5**

B. *Formative Evaluation*

The subject population was comprised of 12 children age 5-11; 3 of the children are ASL signers. Though the project is aimed at deaf children, at this stage of development we are looking for feedback from the target age group in general on overall appeal/acceptability of environments and avatars, ease of navigation and interaction, ability to complete specific tasks, level of engagement, and feeling of immersion. As mentioned previously, evaluation with deaf children will start in Spring 2007. First, a series of interactive math activities/problems, involving navigation and object manipulation, were developed. Then, after a brief demonstration on how to use the program, children were asked to perform scenarios using 'think out loud' protocol while the evaluators collected qualitative and quantitative data. All subjects interacted with the application using the wand because the pinch gloves did not fit the size of their hands; interaction lasted approximately 15 minutes and data were collected in the form of video recordings. Quantitative data included: time spent on each task, number of errors committed while performing each task scenario, number of attempts at solving each problem. Qualitative data included subjects' comments and suggestions, answers to the evaluators' questions, and 'critical incidents', i.e., problems encountered that affect task flow and performance [5].

1. Results

The majority of the children were able to complete the activities on their first attempt; three subjects experienced difficulty moving the virtual clock hands with the wand because '..the hands move too fast ..', and therefore were not able to complete the 'match time' activity. Two subjects showed some discomfort (dizziness and eye strain) with the head tracker and glasses and stopped interacting with the application after approximately 5 minutes.

In general, children liked the appearance of the virtual world and characters, especially the colors and all animated objects such as the gears on the clock store floor, and the moving cakes in the bakery. One subject found the pig character 'scary because too still….he should be making a cake or eating…and his eyes should follow the user..'. Another subject (age 11) suggested that the objects should cast shadows '…and cookies should break when dropped on the floor ..because this is what happens in the real world..'. Four children (age 6-8) commented that the application '..looks much better than a computer game because you feel like you are really there..' and '…this is more fun than learning time from books or real clocks..' Two of the younger subjects (age 5 and 6 and ½) suggested that 'it would be fun to fly around the store….and go inside the cakes and clocks..'

Some problems encountered multiple times by the participants were: the inability to tell which objects were active (some of the subjects' most frequent questions were: 'does this do anything?' or 'can I move this?'); the excessive amount of time between completion of a user's task and the signer's response; the inability to view the signer's feedback multiple times; and the lack of feedback on the application's mode of operation (learning or testing).

V. Discussion and Future Work

The evaluations produced key findings that will be used to modify and improve the design of the application, before the summative evaluation takes place. To summarize, our research has produced results at three levels:

1. Recommendations for improved interaction (i.e., object selection and manipulation, and communication with the system)
2. Suggestions for improved navigation design
3. Recommendations for enhancement of appeal and feeling of presence and engagement

1. In order to improve object selection the experts recommended either a visual indication of selection (highlighting or outlining the objects), or a force-feedback or tactile indication. They also recommended the possibility of selecting multiple objects simultaneously (usability guideline 'Select3' from [27]). To improve the communication between the user and the system, they suggested the inclusion of a virtual control placed in a fixed location in the virtual world that could change its shape or color in order to indicate one of the two modes of operation of the application (learning or testing).

The formative evaluation showed the need to support interface query for users to determine what actions are available for objects. In future iterations, different methods (textual and graphical) for presenting the results of user queries will be explored. Furthermore, the evaluation with children clearly highlighted the difficulty of using the pinch gloves as a means of interaction with the system. In addition to the problem of different hand fits, the pinch gloves allow for input of a very limited number of ASL handshapes. Currently, the research team is developing an improved gesture control system that makes use of a pair of 18- sensor Immersion cybergloves. The cybergloves allow for input of any ASL handshape (because of the high number of sensors) and provide an improved hand fit because made of stretchy material.

2. The experts pointed out the need to include way-finding and alternative travel techniques, once the virtual stores are connected. In regard to way-finding, considered the young age of the target users, they did not recommend the use of virtual maps, because difficult to read. They suggested the implementation of way-finding methods such as following a clearly marked path within the environment (for example a colored line that traces the route), placing visual landmarks, or dropping 'bread crumbs' , i.e., leaving any form of trail markers that can be used by the participants to see where they have been and retrace their steps. These options will be explored in the next design iteration. As far as alternative travel techniques, we have recently programmed the Cobalt Flux Dance Mat [28] to function as a means of locomotion in the FLEX. The dance mat allows the user to move in various directions while stepping on different arrows. This travel

alternative will be assessed in the next iteration of the formative evaluation.

During the formative evaluation, several younger subjects proposed other travel options such as flying and jumping. In the next implementation we will consider including forms of 'wand-controlled' travel. For instance, by pressing a button on the wand (or by making a gesture with the data glove), the participant will be able to jump high into the air and see the virtual world from a higher point of view. We will also include the possibility of going inside certain objects (such as the clocks) to explore how they work.

3. Overall, the visual representation of the virtual world received very positive feedback from both the experts and the children. In particular, children appeared to be drawn to moving and/or active objects, therefore, in future implementations, in order to enhance the visual appeal, we will add more animated objects with increased manipulability. As far as feeling of presence, as perceived through observation, younger subjects (age 5-8) seemed to show a level of immersion and engagement higher than the older ones (age 9-11). This was indicated by their comments, motion, and excitement. Older children commented that some problems, such as objects going through surfaces and inaccuracies with collisions and gravity, break the illusion of '..being really there..' The research team is currently using real-time motion dynamics to solve these problems.

Two of the experts suggested the use of narrative as a key element to increase the users' level of engagement. Based on [29] [30], they proposed to present the children with a general story and with some goal(s) to accomplish, and then let the narrative evolve from the choices of the participants. They also pointed out that interaction is so far limited to navigation and pick-and-place activities. To increase the level of engagement, they suggested to give the children the ability to dynamically alter the virtual world and construct stories as a result of their activities.

VI. Conclusion

In this paper we have presented the user-centered, iterative design approach, and evaluation methodology currently used for the development of a VLE for deaf children. The evaluation framework described in the paper has so far focused on design features and appeal; learning and knowledge acquisition, resulting from the use of the application, will be assessed in a future summative evaluation.

We hope that the methodology outlined in this paper provides a starting point for techniques that allow VR application developers create VLEs that are usable, useful, and engaging.

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