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Prototyping Training Program in Immersive Virtual Learning Environment with Head Mounted Displays and Touchless Interfaces for Hearing-Impaired Learners*

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The purpose of the study was to identify key design features of virtual reality with head-mounted displays (HMD) and touchless interface for the hearing-impaired and hard-of-hearing learners. The virtual reality based training program was aimed to help hearing-impaired learners in machine operating learning, which requires spatial understanding to operate. We developed an immersive virtual learning environment prototype with an HMD (Oculus Rift) and a touchless natural user interface (Leap Motion) to identify the key design features required to enhance virtual reality for the hearing-impaired and hard-of-hearing learners. Two usability tests of the prototype were conducted, which revealed that several features in the system need revision and that the technology presents an enormous potential to help hearing-impaired learners by providing realistic and immersive learning experiences. After the usability tests of hearing-impaired students' exploring the 3D virtual space, interviews were conducted, which also established that further revision of the system is needed, which would take into account the learners' physical as well as cognitive characteristics.

Keywords : hearing-impaired learners, 3D virtual environment, head mounted display, contactless natural user interface, spatial reasoning

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Introduction

Technology-enabled instructional applications can provide students learning experiences that cannot be achieved in a classroom. Furthermore, the applications enable students with sensory impairments to experience and perform various activities at their own pace. Virtual reality, one example of a technology-based application, can present information in multiple modes to allow the students to repeat the learning experience as many times as they require (Smedley & Higgins, 2005). Also, the effectiveness of the virtual learning environment can be determined by the degree of the learner's perceived presence. If the learners perceive a high level of virtual presence, it can encourage them to engage in more interactions with the environment. The virtual presence refers to the subjective sensation of being in a certain environment, which is a computer-generated context (Witmer & Singer, 1998). It is broadly accepted that virtual presence indicates a subjective experience of being in a place even when one is not physically present in that location (Schubert, Friedmann, & Regenbrecht, 2001). In a virtual learning environment, it is important to improve the virtual presence to create a more realistic experience for the learners. If the learners have higher a perception of virtual presence, they might have a sharper sense of being in a learning situation, leading to better learning outcomes.

In this study, we have developed a prototype of an Immersive Virtual Learning Environment (IVLE) in which hearing-impaired learners undergo a training on machining centers by exploring 3D graphics. The prototype can be displayed in a head-mounted display (HMD) to increase the field of view for higher level of immersion and presence, and enable more interactions with the environment. A natural user interface (NUI) was designed to use hand gestures with a leap motion sensor to enable touchless interactions. The virtual learning environment includes a series of complicated machining center exercises in which the participants perform spatial navigation.

Virtual learning environments for special education

Virtual technology can provide various communication systems for visually challenged and hearing-impaired individuals with sensory assistance in multiple ways. There are multiple instances of virtual reality serving the needs of people with disabilities. In fact, virtual reality has long been believed to have enormous potential to assist in the disables, as far back as the early 90's (Powers & Darrow, 1994). There have been many studies that have helped develop multisensory virtual environments for supporting visually challenged learners by incorporating haptic or 3D audio technologies (Connors, Yazzolino, Sánchez, & Merabet, 2013; Lahav, Schloerb, Kumar, & Srinivasan, 2012; Wood et al., 2003), enabling the learners to perceive environments using sensory modes other than vision. However, little research has been conducted to develop 3D virtual environments for hearing-impaired and hard-of-hearing learners.

Many researchers have found that hearing-impaired and hard-of-hearing learners have difficulty in reasoning and abstract thinking due to hearing loss. Limited abstract thinking ability results in an inevitable deficiency in performing cognitive tasks such as solving mathematical problems (Hillegeist & Epstein, 1991), sequential time perception (Eden, 2008; Eden & Ingber, 2014; Ingber & Eden, 2011) and spatial reasoning (Passig & Eden, 2000, 2001). With regard to spatial reasoning, in particular, even with enhanced visual imagery abilities (Emmorey et al., 1993; Klima et al., 1999), hearing-impaired and hard-of-hearing learners are not necessarily capable of conducting inductive reasoning about spatial structures (Passig & Eden, 2000). It has also been reported that hearing-impaired and hard-of-hearing learners find it much more difficult to solve abstract cognitive tasks using visual-spatial schematic representations depicting the relationship between objects (Blatto-Vallee, Kelly, Gaustad, Porter, & Fonzi, 2007).

Based on the potential of virtual reality as an instructional and training tool for learners' spatial rotation (Merickel, 1994), efforts have been made to develop and use immersive virtual reality games to improve the induction of spatial structure among hearing-impaired and hard-of-hearing learners (Passig & Eden, 2000, 2001). From these studies, it was found that virtual reality environments help the hearing-impaired by providing more concrete and immersive learning experiences. However, these studies mainly examined the effectiveness of 3D virtual training compared to 2D and did not include emerging technologies that provide hearing-impaired learners with more engaging visual representations and enhanced interactivity.

In fact, there are many studies that use HMDs for more engaging and immersive virtual experiences (Hoberman, Krum, Suma, & Bolas, 2012). Besides immersive learning experiences, 3D virtual reality applications equipped with the latest technology can also enable hands-free interaction in touchless NUIs (Coelho & Verbeek, 2014), potentially using gesture-recognition technology. There is growing evidence establishing that gestures may enhance cognitive processing (Ehrlich, Levine, & Goldin-Meadow, 2006). Hence, providing a virtual environment for hearing-impaired and hard-of-hearing learners to use their hands to manipulate virtual objects can help them improve their spatial reasoning ability.

Purpose of the study

This study aimed to identify key design features of virtual reality-based training programs with HMDs and touchless NUIs for the hearing-impaired and hard-of-hearing learners. Due to the limited capacity of processing auditory information using only visual resources, hearing-impaired learners need special design features for virtual reality learning environments. Given the non-multisensory nature of learning environments, it is important to avoid cognitively overloading the learners by providing too much visual information. While latest 3D virtual reality technologies allow learners to visually explore more realistic and immersive 3D models, the use of gestures enabled by these technologies for interacting with virtual objects would help learners to proceed learning on their own pace, which might result in reducing cognitive overloads. Two major emerging technologies that were examined in this current study were HMDs and touchless NUIs. An HMD provides an immersive vision with in-depth perception so that the users perceive a high spatial presence. Touchless technology can provide more natural ways of interacting with objects in the virtual environment. However, there is little research that examined whether or not these technologies would be useful for the hearing-impaired or hard-of-hearing students. The touchless NUI with an HMD may not be very effective in such cases because of the visual-only interface. Therefore, the study aimed to identify the key design features required to design an effective 3D virtual environment for the hearing-impaired or hard-of-hearing learners.

Research Methods

Design-based research

The focus of this study was to develop and implement an innovative IVLE for special-needs education and to formulate and adopt a design-based approach for iterative development and refinement of design features in a 3D virtual environment for hearing-impaired learners. A design-based research approach allows researchers to investigate the design and the implementation of innovations while simultaneously developing theories in complex and dynamic environments (Cobb, Confrey, diSessa, Lehrer, & Schauble, 2003).

While collaborating with other stakeholders such as teachers for disabled students and practitioners in the related fields, the researchers developed a design intervention that is responsive to the iterative stages of formative evaluation and redesigns. Typically, this iterative process (Figure 1) follows four steps for analyzing practical problems: developing a solution, testing/refining a solution, and reflecting on produce principles (Amiel & Reeves, 2008). The iterative and responsive process may involve multiple design–test–revise cycles.

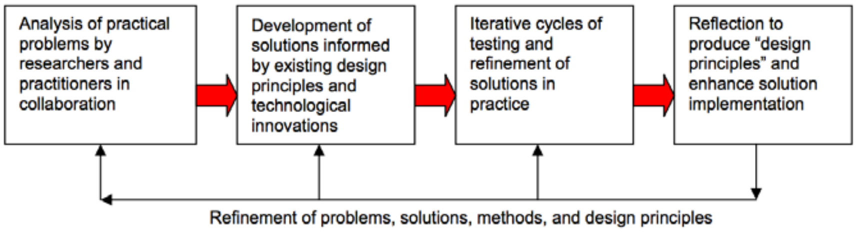

Figure 1. Design-based research (Amiel & Reeves, 2008)

In this project, the design of IVLE evolved through two iterations of evaluation and refinement to transform the prototype into a working application. For the first step, that is, the analysis of a practical problem, we conducted group meetings with trainers of hearing-impaired and hard-of-hearing learners. From these meetings, it was concluded that the IVLE can be applied to build a better training program because it can provide 3D spatial graphics for the learners. We developed an initial solution for the training program followed by two iterative design processes. Iteration 1 aimed to understand the participant's response to the use of an HMD and touchless NUI in a 3D virtual environment. Based on the results from iteration 1, we conducted iteration 2 using an elaborated Virtual Training Center, designed to provide a more realistic vision of the learning environment. Iteration 2 was aimed to minimize potential motion sickness and improve navigational and learning effectiveness among the participants.

Participants

Four hearing-impaired students participated in both the iterations of research and design: one student (24-year-old male) for Iteration 1 and three students (two 30-year-old males and one 20-year-old male) for Iteration 2. All the four participants were 2nd degree hearing-impaired and a sign language translator was participated to conduct the interview process for the participants. Interview questions were discussed with a teacher, who could use sign language, to make the questions not too difficult to understand for the participant. This process was conducted prior to the iterations because it could have been very difficult for the participants to understand extremely abstract questions. The questions were focused on general usability issues regarding the prototypes of the training program.

All the participants were registered trainees in the Korea Employment Agency for the Disabled (KEAD), a semi-governmental organization under the Ministry of Employment and Labor. KEAD provides vocational training and job placement services for the disabled. The participants were hearing-impaired individuals who could communicate with others by using sign languages and text messages. They were Mechanical Engineering graduates and had advanced skills to operate machines and were well prepared for suitable employment. In addition, they also had some gaming experience.

Virtual reality programming and setup

We designed and developed the prototypes of the training program in the IVLE. For display, an Oculus Rift Development Kit 2 (DK2) was connected to a 64-bit computer (HP Z440 Workstation, Intel CPU 5th generation, 32GB Ram, NVIDIA GeForce GTX GPU, 512GB SSD) running Microsoft Windows 10 (64-bit). The graphical objects used in the virtual training center were either developed by Sketchup Pro or downloaded from the website 3dwarehouse.sketchup.com. We used the same 3D model of Computer Numerical Control (CNC) machines used in the actual training modules in the KEAD. The Unity 3D was used to develop the IVLE, which is one of the most popular game engines. For the touchless NUI, which was an input device for a hands-free interface of IVLE, we applied Leap

Motion (www.leapmotion.com), a new 3D interaction technology that tracks the position and orientation of hands, fingers, and palms. We integrated the unit with an HMD and touchless NUI to deliver an embodied experience to the participant.

Design features of IVLE

Learning how to operate a machining device is not only critical for job placement of the learners, but also particularly challenging since the learners cannot see the insides of the machine, which prevents them from visualizing a series of movements and operations that produce the final product. Hence, we designed our study to enable users to explore both the exterior and the interior of the machine (see Figure 2). In the IVLE, the learners could virtually enter the machine's interiors and explore the 3D structure by moving their own head using an HMD. In addition, learners could zoom in and out, tap, grab and rotate the projections using hand gestures.

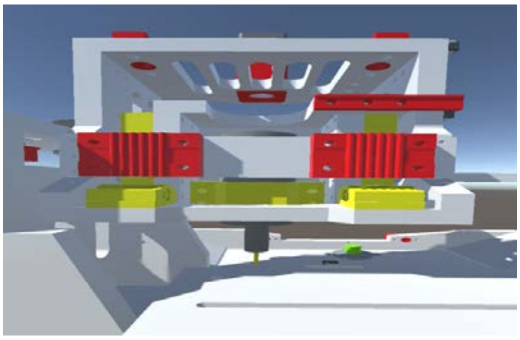

Figure 2. Insides of a CNC machine in the 3D virtual environment

HMD

In order to provide more immersive 3D visual graphics, we used a developer kit version 2 from Oculus as an HMD system. Introduced in late 2012m, the HMD (Oculus Rift) has a 100-degree field of view with a stereographic view. The Rift has a 3D inertial sensor to track and monitor head movement so that the objects can be displayed in the direction of the user's gaze in an immersive VR environment(Xu, Chen, Lin, & Radwin, 2015). With the head tracking system, the participants can virtually interact with the objects.

Touchless NUI

The device can detect hand gestures from about 3 cm up to 50 cm from the device. Its field of view extends to nearly 150 degrees above the device. Thus, the user only needs to place his hands in the hemisphere (Nabiyouni, Laha, & Bowman, 2014). We introduced the leap motion technology in the Oculus Rift to integrate the HMD and touchless NUI. Figure 3 shows how the touchless NUI is mounted on the HMD.

Figure 3. Integration of HMD (Oculus Rift) and touchless NUI (Leap Motion)

Virtual training center

The IVLE was implemented in a virtual learning center, which was designed to simulate a physical training center with several rooms. This virtual training center had four sections for the students: 1) help desk 2) lecture room 3) tool checking room and 4) machine room. Figure 4 shows a floor map of the virtual training center. The help desk displays the locations and purposes of each section.

In the lecture room, the learner received instructions on how to use the navigational function with the joystick and the interactive function with the NUI. Participants watched PowerPoint slides to understand how to use the joystick and interactive gestures and studied the floor map. In the tool checking room, participants were given instructions on what to do with several tools during the machine training. In this room, the participants were given an opportunity to explore and familiarized themselves with the tools that they would use in the machining center, represented virtually as the machine room (Figure 5).

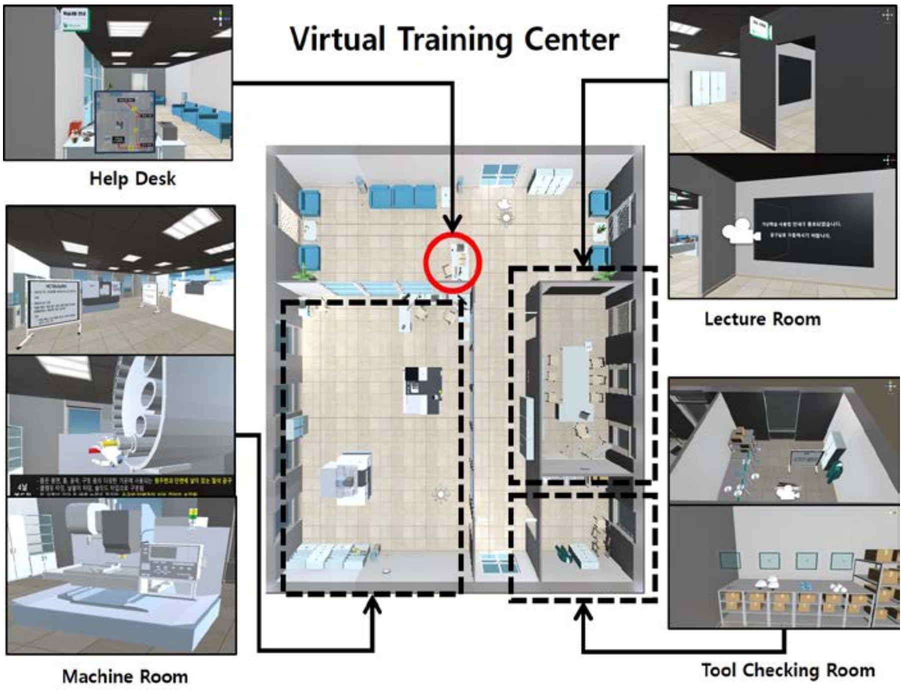

Figure 4. Floor map of virtual training center

Figure 5. Lecture room (left) and tool checking room (right)

In the learning module, the participants started the module by visiting the help desk to find out the section they needed to visit in the IVLE (See Figure 6). Subsequently, they proceeded to the room in which a machine center was placed. Figure 6 describes an actual machining center used for the vocational training of the participants. The participants could switch their views between the exterior of the machining center and the inside structure showing how the parts were placed.

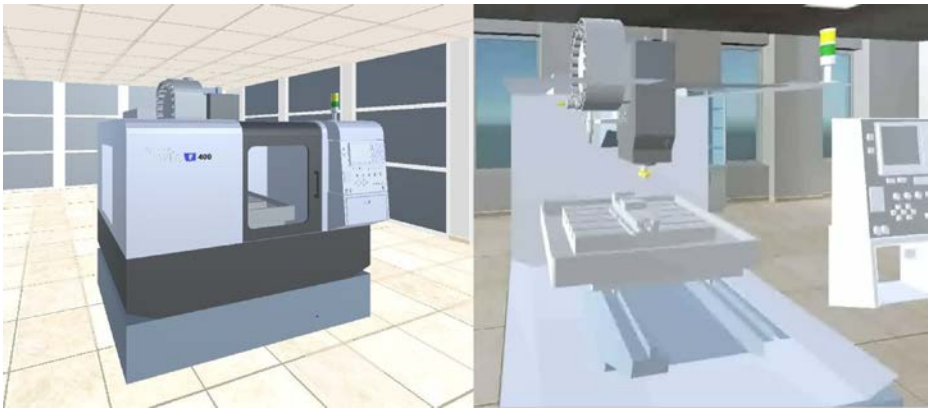

Figure 6. Outside (left) and inside (right) of CNC machine

Results

Iteration 1: Integration of HMD and touchless NUI

Process of usability test

The use of an HMD and touchless NUI in a 3D virtual environment for hearing-impaired learners is relatively new. Taking into account the special characteristics of hearing-impaired learners' with regard to their physical and cognitive functions, it is necessary to conduct the usability test to examine how they interact with the virtual environment using an HMD and NUI. Previous studies showed that HMD frequently results in motion sickness among users due to the instability of their standing postures (Merhi, Faugloire, Flanagan, & Stoffregen, 2007). Thus, in this study, we tried to examine how hearing-impaired learners would feel in the 3D virtual environment when they used an HMD.

In addition, since a touchless NUI is a new method for navigating virtual spaces, a usability test has to be performed to investigate its relative advantages or disadvantages compared to existing input devices. In this study, a Leap Motion sensor was compared to an Xbox game controller. Previous studies compared Leap Motion to a mouse in terms of its interactivity with virtual objects (Coelho & Verbeek, 2014). However, since wearing HMD does not allow users to easily locate and use input devices, we used an Xbox game controller that could be held in the users' hands to compare with a Leap Motion sensor.

Figure 7. Controlling the 3D virtual environment with Oculus Rift and Leap Motion (left) and controlling the 3D virtual environment with Oculus Rift and Xbox controller (right) during the Iteration 1

Since the first usability analysis focused on which specific features the users were using when they were operating a touchless NUI while wearing an HMD to interact in the IVLE, a simplified machining model was used in the test. Before collecting usability test data, a researcher verbally explained the task to a participant and it was translated into sign language. He was instructed to observe any physical/psychological inconveniences or discomfort expressed by the participants during a virtual experience. For the usability test, a participant was asked to freely explore the interior and exterior of a CNC machine in the 3D virtual environment using several variations of the system – seated vs. standing posture and touchless NUI vs. Xbox game controller (Figure 7). After the free exploration, a researcher asked open-ended questions regarding the experiences of using the system with different postures and input systems and tried gauge the participant's experience in terms of a sense of reality, immersion, and aesthetics of the 3D virtual environment.

Perceived pros and cons of HMD and touchless NUI

Overall, the participant rated the 3D virtual environment as realistic and immersive. For the question regarding the perceived reality of the CNC machine in the 3D virtual environment, the participant answer gave a Likert rating of 4 and observed that "I found the CNC machine realistic". He found the environment very immersive (5 out of 5) and was satisfied with the color and design (5 out of 5). These results were consistent with the previous studies showing the potential of HMD in providing immersive and realistic experiences. Furthermore, in order to test the usability of HMD, we asked the participant to explore the 3D virtual environment in seated as well as standing postures. The participant reported that the nauseous feeling was more prominent when he was standing, more so when he looked at an object from a height. In such cases, he reported a feeling of disorientation due to the discrepancy between the depth of the floor he was actually on and the floor that he perceived in the virtual space.

This is consistent with previous studies reporting that HMD produced more motion sickness in a virtual environment than other types of display (e.g., computer monitor) (Sharples, Cobb, Moody, & Wilson, 2008). Further, this motion sickness tends to be higher when the user is standing compared to when he is seated (Merhi et al., 2007). Assuming that the hearing-impaired and hard-of-hearing learners might experience more motion sicknesses than regular learners due to their hearing deprivation, further investigation is required to provide a safer and more comfortable 3D virtual experience to the hearing-impaired.

Preference for navigation method and motion sickness

When the participant interacted with a CNC machine in the 3D virtual space by using an Xbox game controller and a Leap Motion sensor, he exhibited a preference for a game controller because of his familiarity with the device. However, he also liked using the Leap Motion sensor that enabled tapping on a specific part of the machine with his fingers for receiving instructional information (e.g., the name of each part). Additionally, it was noted that it would be beneficial to have a feeling of tapping/grabbing or tools being properly fixed in the machine when he interacted with the virtual object through haptic feedback. Incorporating haptic feedback would not only enhance realness and immersion in the virtual space but also provide a substituting sensory feedback (haptic) for hearing-impaired learners who cannot receive feedback from auditory channels. Overall, using a Leap Motion sensor was perceived as being slightly demanding because of the unfamiliarity with a new device. Prior training would help users to overcome the discrepancy between the actual and the perceived distance from the hands to an object.

The participant felt motion sickness when he used the IVLE in a standing posture which led to more variations in gazes. He also pointed out the usefulness of both input devices– a game joystick for more familiar navigation and NUI for object manipulation. He also suggested reception of a confirmatory feedback (preferably with haptic) when an object was selected in the IVLE. Consequently, our design was revised for Iteration 2 to provide learners an enhanced experience following the learnings from Iteration 1. These design changes are discussed in the next section.

Iteration 2: Navigation, virtual presence, and perceived learning effectiveness in training and learning modules

Design changes implemented for Iteration 2

Based on the findings of Iteration 1, we refined the design of IVLE for Iteration 2. First, in order to reduce the learners' motion sickness, we tried to minimize possible eye gaze movements during navigation by allowing the learners to be seated while in the virtual space. In addition, we shortened the duration of each instructional module to less than 15 minutes so that participants could take a rest between two modules. While we could not provide haptic feedback for a feeling of grasp and touch in this early stage of development, we incorporated visual feedback that highlighted a selected part when participants touched a virtual object to provide them a better sense of interaction. To reflect the participant's positive feedback for both input devices, we allowed participants to use the Xbox game controller when navigating the virtual space while using their own hand gestures with the Leap Motion when they needed to touch the object in the virtual space.

Figure 8. Controlling instructional information by using touchless NUI

In Iteration 2, training and learning modules were included in the IVLE and more authentic learning contexts were embedded in two modules with enhanced realistic models of a machining center. Even though we revised our design to accommodate the needs of hearing-impaired learners in their use of new devices (HMD and NUI), we still needed to explore the efficiency with which they can navigate through and complete tasks in the 3D virtual environment. In addition, considering that the sense of virtual presence has been perceived to be an important factor influencing learning in the virtual space (Schubert et al., 2001; Witmer & Singer, 1998), whether or not hearing-impaired learners could perceive virtual presence while navigating and interacting with the virtual environment was examined. Lastly, in order to investigate how effectively they perceived the overall experiences in the virtual environment, a survey for the learners' perceived learning effectiveness was included in the usability test.

Before conducting a usability test for training and learning modules, participants were first instructed how to use Oculus Rift, Xbox Controller, and Leap Motion sensor for ten minutes following the protocol of the usability test. Subsequently, they explored two modules in the IVLE, each lasting lesson than 15 minutes, followed by interviews. Figure 8 shows a participant using the Leap Motion to scroll on-screen texts to read the description.

Individual factors

The usability test results revealed that there were some differences in the time spent for task completion, perceived virtual presence, and perceived learning effectiveness based on the individual learner's prior experience in 3D virtual gaming. The more experienced 3D game participants needed lesser time for task completion. These users also perceived a lower level of virtual presence than those who had lesser experience with 3D gaming. On the perceived effectiveness of learning, the participants noted that the IVLE was more effective in presenting 3D visual-related learning content rather than traditional text-based learning materials. The results of this study revealed that the 3D virtual environment in combination with emerging technologies has a potential to help hearing-impaired learners by providing realistic and immersive experiences with concrete 3D virtual objects. However, there were differences in the expectations and application of a 3D virtual environment, depending on the learners' level of prior learning and experience of 3D virtual gaming. Further revision of the developed IVLE is needed by taking into account the learners' physical as well as cognitive characteristics.

Additional design implications for the IVLE

While we found differences in time spent for task completion, perceived virtual presence, and perceived learning effectiveness, different participants also had a few common observations regarding the design features of the IVLE they explored. Overall, they were satisfied with visual images that represented realistic CNC machines. However, a need to revise on-screen text explanations was established. For example, participants observed that on-screen explanations needed to be presented close to the relevant visual representations, with a shorter length that can be seen without scrolls and comprising minimal text. These characteristics are due to the nature of current IVLE developed for this study that focuses on hearing-impaired learners. Since voice narrations could not be provided in the IVLE, instructional contents were provided with on-screen texts, which is against the modality principle that recommends the use of audio narration and visual images (Moreno, & Mayer, 1999). However, segmenting on-screen texts to be presented one at a time (Segmenting principle) and placing them close to visuals (Spatial contiguity principle) might enhance essential information processing in virtual learning environments as in multimedia learning situations.

Discussion

Embodied cognition in the virtual learning environments

Horizon Report: 2016 K-12 Edition (Adams Becker, Freeman, Giesinger Hall, Cummins, & Yuhnke, 2016) introduced VR as one of the six important developments in educational technology and highlighted that VR could overcome current shortcomings of education including the lack of concrete experiences by fostering more engaged and authentic learning opportunities. In an effort to contribute to this new and evolving area of research, we proposed the design process and evaluation methods used in the development of IVLE for hearing-impaired learners. Although the design approach and evaluation results are specific to our application, they could be used as guidelines for design and evaluation of similar virtual reality learning environment. In fact, with the recent theorization of embodied cognition that emphasizes the learners' perceptual and bodily experiences in understanding abstract concepts (Barsalou, 2008; Smith & Gasser, 2005), providing direct perceptual experiences has been emphasized in learning (e.g., Han & Black, 2011) and there has been an ongoing effort to incorporate emerging VR technologies that can possibly provide more direct immersive learning experiences. For example, the use of Oculus Rift allows learners to interact with virtual objects from a first-person perspective with a 3D inertial sensor that tracks and monitors head movements so that the objects can be displayed in the user's gaze direction in an immersive VR environment (Xu, Chen, Lin, & Radwin, 2015).

Effects of NUI

Further, the natural use of hand gestures in manipulating virtual objects also enhances the learners' cognitive processing, especially when they are congruent with the concepts being learned (Segal, Tversky, & Black, 2014). Considering that hearing-impaired learners lack spatial reasoning abilities (Passig & Eden, 2000, 2001) and inductive reasoning about spatial structure (Passig & Eden, 2000), such direct experiences in virtual spaces would enhance their spatial learning. However, little study has been done towards designing and developing 3D virtual environments for hearing-impaired learners. We hope that this study can provide implications on how emerging technologies can be used to help physically disabled learners.

Limitations of study

However, this study also has limitations inherited by the population that we worked with. Since learners with a physical disability are minorities who need to be researched with more restrictions, we were only able to work with a small number of male participants for this study, which leads to an issue of generalizability of the result. Further, hearing-impaired learners showed some characteristics in information processing that was not fully addressed in this study. From the interview, we noticed that the hearing-impaired and hard-of-hearing learners were highly sensitive to visual information in general. For instance, one of the participants preferred faster movement of the object when he zoomed in/out. According to previous psychological studies examining hearing-impaired learners' visual information processing, signers have enhanced imagery abilities that are accounted for by their use of sign language compared to hearing-impaired non-signers and hearing learners (Emmorey, Kosslyn, & Bellugi, 1993). While this is consistent with the feedback that we received from our participant who used sign language, we could not reflect this in our design due to the lack of prior design research focusing on the use of virtual environments in special education. Considering that this area of research is still very new and emerging, more in-depth examination of the learners' experiences depending on their characteristics is necessary.

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