Grasping the Future: Virtual Hands Control for Fine Motor Tasks

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ABSTRACT

Immersive Learning Simulations (ILS) focus extensively on the production of visually and behaviorally realistic characters and environments, sometimes with interactive support from gross motor input devices such as gaming treadmills. However, realistic visualization, behavior, and interaction of hands in these simulations are often minimized in favor of generalized or rigid animations that limit fine motor training possibilities. While unrealistic portrayal of these essential human communication and interaction tools could be attributed to a lack of practical technology, new generations of affordable and available technologies now enable high-fidelity hands visualization, behavior, and interaction. These technologies will change the way that learners express body language, manipulate virtual objects, and project presence within ILS.

This study summarizes our experimentation with virtual reality head-mounted displays, gesture recognition, and haptic feedback to mediate fine motor hand interaction to psychomotor domain tasks and reports measurements of learner presence. A use case is provided to ground discussion around a problem-based learning approach with respect to disassembly of military equipment using fine motor interaction techniques the learner can see, feel, and hear. Cognitive task analysis and thinking out loud protocol are used to elicit and report learner measures of presence. Research related to the psychomotor and cognitive underpinnings of our embodied learning environment design is presented reader consideration. Finally, we discuss the strengths and weaknesses related to our technical and interactive design approach and provide recommendations for future research.

ABOUT THE AUTHORS

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Schawn Thropp is a Technical Research Fellow at CTC with 21 years of experience in creating software applications and performing research and development for the U.S. Government. At CTC he is the technical lead for the Immersive Environments Platform and is focused on researching, developing and studying technologies that blend the digital world with the physical world around us. Mr. Thropp's interests include augmented reality, user profiling, personalization of data and services and the impacts of the evolving Internet of Things.

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INTRODUCTION

This study was designed to measure learner *presence* using virtual hands control to complete cognitive and psychomotor domain equipment maintenance tasks on a 3D equipment model within a Cognition and Dexterity Virtual Reality (CogDex) experimental training system. Slater and Wilbur (1997) defined presence as a person's subjective and objective state with respect to an environment where their subjective state relates to their evaluation of the degree of "being there" and where their objective state relates to the extent to which individuals behave in a Virtual Environment (VE) similar to the way they would behave in similar circumstances in everyday reality. Psychomotor domain tasks encompass skill requiring the use and coordination of skeletal muscles, as required of physical activities (Morrison, Ross, Kemp, & Kalman, 2010). For the purposes of the current study imitation of the physical gestures related to equipment maintenance activities were of interest and not precise articulation. Specifically, the gestures of interest were designed for execution within a visuospatial task orientation though simulation and interaction of physical maintenance routines within a realistically modeled VE.

Participants were tasked to disassemble a 3D Helicopter Mission Kit (HMK) model by following a procedure displayed on an exercise progression screen and with referential support from an S1000D technical manual provided through diegetic interfaces positioned within the VE. The experimental system was designed to incorporate a Head-Mounted Display (HMD) and HMD-mounted hand tracking sensor that enabled participants to use the natural motion of their arms and hands to interact with HMK model components in Virtual Reality (VR). Results of a Presence Questionnaire (PQ) administered to HMK expert practitioner-participants indicated that learners experienced a moderate-high to high level of presence when using the experimental training system.

Background

The human perceptual system employs inference in order to make best guesses as to the state the world and the state of the self through synthesis of sensory inputs. VE designers have long used this knowledge in an attempt to move learners to suspend disbelief that the experiences they portray are actually real by stimulating the visual, auditory, tactile, olfactory, and gustation senses. When the learner is situated within a simulated world that is designed to be perceptually convincing then the learner is able to experience spatial immersion and may achieve a measure of presence (Adams, 2004).

Psychomotor and visuospatial training research is of ongoing interest in the medical community where hand dexterity is critical in surgery and other procedures. For example, a study by Hendrie, et al. (2016) was conducted to determine if learning laparoscopy psychomotor skills in a transparent shoebox and laparoscopy visuospatial skills in VR separately and sequentially might offer an efficient alternative to current training. The study found no support for the need to separate these training aspects. With the rise of new gesture detection sensors, the current study seeks to understand the relationship between measures of learner presence and the application of realistic virtual hands to visuospatial tasks for equipment maintenance training in VR.

Research Question

How does the application of virtual hands control for visuospatial tasks effect measurement of presence within a VR equipment maintenance training simulation?

EXPERIMENTAL DESIGN

Physical Environment

Experiments using the training system were conducted within a computer laboratory setting containing an experiment PC and HMD. Participants were allowed to stand or sit at the PC at a minimum distance of three feet to a maximum distance of five feet. The participants were allowed to move around this area so long as they remained in front of the head tracker, which was necessary to translate and orient the view field to view the 3D HMK model from needed locations and angles.

Cognitive Task Analysis

A Cognitive Task Analysis (CTA) was performed to capture and analyze the behavior and overt actions of an exemplar practitioner performing a series of maintenance procedures with the HMK. Over the course of the CTA a disassembly procedure was identified for inclusion as a task in the study. The task represented a cross-section of typical steps and motions required of a HMK maintenance task including manipulation of fasteners and the decoupling of parts. The CTA was further elaborated with support from an S1000D technical manual detailing the preparation, management, and use of the HMK.

While learner cognition is an important part of the experimental training system, it is not the focus of our study. However, to summarize design intent in a fully realized system with respect to cognition we anticipate the system to support the upper levels of Bloom's Taxonomy with respect to application, analysis, synthesis, and evaluation as learners will actively apply knowledge within realistic and dynamic contexts (Morrison, Ross, Kemp, & Kalman, 2010). Similarly, we anticipate the system would support levels 3-4 of the Interactive Multimedia Instruction model with respect to complex and real time participation.

Population Sampling

A participant sampling frame *(N=3)* of CTC personnel working on the design, development, and maintenance of the HMK system were selected from CTC's Advanced Engineering & Manufacturing Group.

Hardware and Software

The experimental training system was developed and deployed using an Alienware Area 51 PC running Windows 8.1. VR visualization was provided using the Oculus Rift Development Kit 2 HMD and hand tracking was provided using a Leap Motion sensor affixed to the front of the HMD using a specialized plastic mount.

The Unity game engine personal edition was used to integrate the experimental training system exercise event sequencing, models, sound, and virtual hands interaction. Unity provides native virtual reality support for the Oculus Rift and served as the integration point for the Leap Motion Orion Beta software development kit, which is a being developed expressly for HMD-mounted hand tracking. Table 1 lists the hardware and software used in this study.

Table 1. System Specifications

Hardware	Software
Alienware Area 51 PC	Windows 8.1 x64 Edition
Leap Motion	Leap Motion Orion Beta SDK 3.1.2 for Windows
Oculus Rift Development Kit 2	Oculus Rift Runtime 1.10
	Unity 5.3.4
	Unity Core Assets for Leap Motion 4.1.1

Visualization Design

Attainment of high measurements of presence are more likely when leveraging precisely calibrated hardware and software components that are tuned to performance characteristics that tightly emulate visual sensory stimuli. Abrash (2014) discussed what hardware performance attributes are required to achieve presence in virtual reality, including: (a) A minimum 80° field of view; (b) minimum resolution of 1080p; (c) maximum low pixel persistence of 3ms; (d) refresh rate of 60-95 Hz; (e) simultaneous illumination of all pixels; (f) two optical lenses; (g) optical calibration; (h) tracking translation within 1mm accuracy and orientation within .25°accuracy. The HMD used in the study met or exceeded all of the criteria outlined by Abrash.

The experimental training system incorporated binocular and monocular cues to support depth perception. Binocular cues were provided using the native stereopsis support of the HMD through its arrangement of lenses. High convergence of vision on objects was provided through the design of the VE in which the learner is situated less than 1m from the HMK model and shadow stereopsis is similarly enforced through the lighting design of the VE. Monocular cues were provided through design of the VE and were designed around near-field depth perception including absolute size, accommodation, perspective, relative size, curvilinear perspective, texture gradients, lighting and shading, and defocus blur. For participants that are familiar with the HMK, familiar size may also help them to predict the depth of the model (Vishton, 2011).

Thresholds for perception of fluid motion in gaming environments are reported to be between 13ms, at the fastest possible speed at which humans can perceive motion, and 50ms (Burger, 2015). For the current study, the visual latency of the movement of tracked arms and hands were portrayed at greater than 35ms per frame allowing optimal motion-to-photon latency at a minimum of *120* Frames Per Second (FPS) (Leap Motion, 2015). The minimum tolerable FPS for the illusion of motion is 24, while a FPS of 60 produces very smooth motion. By measuring the performance of the VE we found that the FPS and millisecond per frame measurements *(FPS=78; ms=13)* were within both the 24-60, or greater range and 13-50ms range.

Interaction Design

In order to provide participants with vestibular cues informing of the position of their bodies in space the experimental training system incorporated head tracking, limited by the length of the HMD cable and head tracker range of approximately 5 feet (Colavita, 2006). Participant kinesthetic cues were achieved by incorporating the natural movement of arms and hands to activate the muscles, tendons, ligaments, and corpuscles responsible for reporting action potentials to the proprioceptive system. The experimental training system hand tracking sensor accurately tracked and portrayed most participant hand movement in the VE. Low latency portrayal of arm, hand, and whole body movement was highly correlated to real arm, hand, and head movement during visualization; further reinforcing the perception interactions in the VE were real. Figure 1 shows the realistic portrayal of arm and hand motion and Figure 2 depicts the visual and kinesthetic Human-Computer Interface (HCI).

Figure 1. Realistic Arm and Hand Motion

Figure 2. Visual and Kinesthetic HCI

The experimental system's interactive components were comprised of two subcategories including fasteners and parts. Fasteners were defined as any object that holds two or more parts together, such as screws or bolts. Parts were defined as any object that may be separated from the whole model other than fasteners, such as cover plates and light bulbs. Participants interacted using the hand tracking sensor through three methods including callout, detachment, and decoupling, described below:

Callout - By gazing at or placing index finger on a component its name was displayed in a callout.

Detachment - By placing an index finger on an active fastener, indicated using a flashing material cue, the fastener would transfer from an attached state to a detached state and display a detachment animation.

Decoupling - By pinching an active part, indicated using a flashing material cue, and moving the hand the part would be decoupled and translated to the desired location where the pinch would be released.

Method

Candidate participants *{p1, p2, p3}* were administered a short demographic survey designed in order to characterize the sampling frame, with attention to their knowledge of the HMK. The results of the demographic survey are displayed in Table 2.

Table 2. Demographic Survey Results

Demographic	*p1*	*p2*	*p3*
Gender	Male	Male	Male
Age	*50-64*	*50-64*	*50-64*
Level of education	College	Some College	Post graduate
Familiarity with HMK components	Very familiar	Very familiar	Very familiar
Years worked with HMK components	*6+*	*6+*	*6+*
Expertise assembling/disassembling HMK components	Expert	Expert	Journeyman

Candidates were administered a subset of the original Immersive Tendency Questionnaire (ITQ) order to determine preexisting disposition to immersive environments. The ITQ measures levels of involvement in common activities as it is theorized that individuals who tend to become more involved in these activities will also have greater tendencies towards immersion. Historically, ITQ scores are highly correlated with scores obtained from the PQ in the same populations (Witner & Singer, 1998). A seven-point scale was used to collect reported measures of tendencies from a score of one indicating low tendency to a score of seven indicating high tendency. Questionnaire items were grouped according to norms including *focus, involvement, emotions,* and *games*. Candidates predominantly indicated a low to moderate level of immersive tendency, which indicated that PQ scores should be highly correlated for the sample frame. Measures of candidate average response to the ITQ by norm are displayed in Table 3.

Table 3. Candidate Average Responses to ITQ by Norm

Norms	*p1*	*p2*	*p3*
Focus	*4.1*	*3.8*	*5.0*
Involvement	*1.8*	*2.0*	*2.6*
Emotions	*2.0*	*1.5*	*3.0*
Games	*1.0*	*1.6*	*2.3*

Appendix A depicts PQ items with respect to the experienced environment, included sounds, and sense of touch. They are grouped according to norms including realism, possibility to act, quality of interface, possibility to examine, self-evaluation of performance, sounds, and haptic. The PQ has been long employed in studies of presence and was designed based upon empirical review of presence science and based upon factors posed by the presence research community and has been evaluated for consistency (Witmer & Singer, 1998). Selected participants were administered a subset of the original PQ at the conclusion of the task session using a seven-point scale to collect

reported measures of presence. A score of one indicates low presence and a score of seven indicates high presence. The scale is reversed for items 14, 17, and 18. Results of the PQ are described in the results section.

Disassembly Task Session

Participants were briefed on the HMK disassembly task, equipment, and thinking out loud protocol guidelines. To ensure that the VE was clearly visible, participants who wore glasses were given the opportunity to telescope the HMD to accommodate for the space their glasses occupied. Participants who could not wear their glasses with the HMD chose HMD lenses to accommodate their sightedness, including normal and near.

The participants were then asked to complete the task which included disassembling components to reach a light bulb, as is typical of a common HMK maintenance task. Specifically, the participant would need to remove nine fasteners to detach and decouple two parts to expose the light bulb. The full task is represented as follows, with non-attribution of specific component names due to design sensitivity of the HMK: (1) Locate part 1, (2) remove 7 fasteners from part 1, (3) decouple part 1, (4) locate part 2, (5) remove 2 fasteners from part 2, (6) decouple part 2, and (7) observe light bulb. Figures 3 and 4 show examples of the detachment and decoupling interaction mechanics depicted using a V-twin engine model, as design sensitivity prohibits depiction of the HMK model.

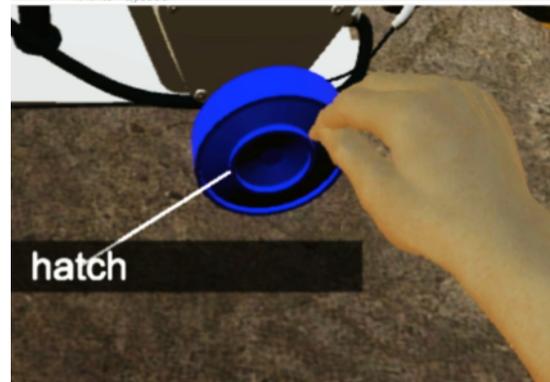**Figure 3. Detaching a Fastener by Pointing**

Figure 4. Decoupling a Part by Pinching

RESULTS

Measurement of Presence

The study found that participants predominantly reported moderate-high to high measures of presence in their experience with the experimental training system. This result was significant and unexpected given the historically high correlation of ITQ scores to PQ scores. Recall that the average ITQ scores for our participants indicated low to moderate measures of presence, from which we predicted that participant PQ scores would be highly correlated. Measures of participant average response to the PQ are displayed in Table 4.

Table 4. Participant average responses to PQ by norm

Norms	*p1*	*p2*	*p3*
Realism	*7.0*	*6.6*	*6.6*
Possibility to act	*7.0*	*7.0*	*6.3*
Quality of interface[1]	*1.0*	*1.7*	*3.0*
Possibility to examine	*7.0*	*6.7*	*6.3*
Self-evaluation of performance	*7.0*	*6.5*	*7.0*
Sounds	*7.0*	*7.0*	*4.3*
Haptic	*7.0*	*7.0*	*DNA*

Note: [1] = reversed scale, *DNA*= did not answer

Thinking Out Loud Analysis

Participants were asked to vocalize what they were thinking during interaction with the experimental training system. Interestingly, few references were made towards basic interaction mechanics such as "I'm touching the fastener," or "I'm pinching and removing the part," and any problems interacting therein. Instead, most references regarded the user interface and level of realism. In reviewing participant PQ scores for measures of presence, we posit that such muted feedback about general interaction problems might be owed to high PQ scores across norms and the natural modeled visual and kinesthetic portrayal of the these interaction methods. Data collected using thinking out loud protocol for each participant were codified using the PQ subscale model and are presented in chronological order in Table 5.

Table 5. Thinking Out Loud Protocol Data Collection

P1 Vocalizations	Subscale
t1. "Wow pretty neat….part number popping up when I look at a part... wow!"	Interface Quality
t2. "Really looks like my hand!"	Realism
t3. "Oh cool!" (When power tool sound played when removing fastener)	Auditory
t4. "Focus seemed to go squirrelly when I turned my head to the side and then back again."	Involvement/Control
t5. "Manual seems to be in the way."	Interface Quality
t6. "The positioning of part numbers could be adjusted so they don't cover the bolts."	Interface Quality
P2 Vocalizations	**Subscale**
t1. "Oh cool!" (When hands came into the scene)	Realism
t2. "The manual is getting in the way."	Interface Quality
t3. "Is there a difference in the hands?" (looking at both hands through HMD)	Realism
t4. "I like the (exercise) progression screen."	Interface Quality
t5. "I have no problems manipulating the objects in the scene." (Rolls chair to new location)	Haptic
t6. "Why does the finger look bent when I try to touch the screws?"	Realism
t7. "I can see all the pieces real easy."	Realism
P3 Vocalizations	**Subscale**
t1. "I wear bifocals, but can get away with a lot from the visual perspective. I can read the manual text."	Interface Quality
t2. "As I move my hand forward the fingers bend."	Realism
t3. "Shoulder was under the tech manual…felt weird knowing that."	Realism, Interface Quality
t4. "Having real (looking) hands helps make me feel immersed."	Realism

Note: tn = time segment.

Data collected from thinking out loud vocalizations were allocated to the following PQ subscale categories for qualitative analysis: auditory, haptic, interface quality, involvement/control, and realism.

Auditory - Only three sounds were provided within the experimental training system including an ambient helicopter repair bay noise, the sound of a power drill initiated when a fastener was decoupled, and a metal clank noise initiated when parts were decoupled. One participant ($p1_{t3}$) liked the correlation of the visual event of detaching a fastener with the sound of the power drill.

Haptic – With regard to the part-pinching and translation mechanic, one participant ($p2_{t5}$) noted that there was no problem in manipulating the parts in the scene.

Interface Quality - With respect to interface quality and callouts participants ($p1_{t1}, p1_{t6}$) found the automatic callout of part names upon gaze or touch to be useful. However, the positioning of the callouts sometimes could obscure components behind the callout. With regard to the S1000D technical manual, participants ($p1_{t5}, p2_{t2}$, p3$_{t3}$) felt that it was positioned too close to the HMK work space and one participant was afraid to bump into the manual with their right shoulder. The fixed diegetic manual screen could be detached and repositioned by participants by gazing at or touching a detach/attach screen button while using head orientation to place the screen elsewhere in the world,

however this instruction was not given ahead of the task as it was incorrectly assumed that the manual screen were suitably positioned. One participant ($p2_{t4}$) noted that the diegetic exercise progression screen was helpful in their task.

<u>Involvement/Control</u> - One participant ($p1_{t4}$) experienced a problem with head tracking that caused visualization of the scene to "jump" as tracking was eventually resumed. This was likely caused by obfuscation of the HMD from the head tracker as the participant moved their head too low and behind a table.

<u>Realism</u> – Participants ($p1_{t2}$, $p2_{t1}$, $p3_{t4}$) made statements and or produced reactions that indicated that hand models appeared to be real. One participant ($p3_{t4}$) made a direct reference to their feeling of presence, stating that the realistic looking hands helped them feel immersed. One participant ($p2_{t3}$) inquired about differences in the left and right hands portrayed and it was explained that there is not and that either hand were equally capable of completing the task. Another participant ($p2_{t7}$) noted that they could easily see all the pieces of the HMK from their respective viewing angle, as they would expect in the real world.

Participants ($p2_{t6}$, $p3_{t2}$) noted that, as they would reach their hand forward to activate fasteners that the index finger would sometimes be visualized with a significant and unintended downward bend. It's important to note that the fasteners were positioned at a low point in the VE and, correspondingly, the hand had to be moved to a low point in the physical world to complete the activation. As the hand moves farther forward and then down the index finger becomes obscured by the upper part of the hand, limiting the ability of the hand tracker to track the position of the index finger. A simple solution to this issue would be to instruct learners to not extend the arm so far forward while performing the associated interaction and instead move the body closer to the objective fastener, thus allowing the hands to stay within stable tracking range of the hand tracking sensor.

DISCUSSION

Within our formative study it was found that our sampling frame of expert practitioner-participants reported moderate-high to high measures of presence in the PQ. This result was in opposition to low predicted measures of presence as indicated by the ITQ. This finding begs the question of how would the same sample frame fare in the PQ if the study were replicated in VR, but without benefit of virtual hands control? If the outcome of the new study indicated the predicted low to moderate-low measures then we could further theorize as to the specific nature of effects of virtual hands control towards measures of increased presence.

The average age of the participant sample was within the 50 to 64 range, making them significantly older than operators and technicians aged 20 to 30 who might use such a training system. For example, it is worthwhile to note that all participants wore glasses, however all were able to either wear their glasses with the HMD, or not, fortunately while still reporting clear visualization of the VE. There are gradual, age related perceptual deficits that occur in the 50-64 year old demographic with regard to perception of and reaction to movement (Colavita, 2006). While the results of this study indicate that the illusion of arm and hand movement were highly correlated, we must wonder what the results of the experiment would be if administered to their younger counterparts.

Due to constraints upon time to complete the experimental training system and to secure a sampling frame we were unable to obtain a larger sample of practitioners that worked with the HMK in the real world, who may possess differing disposition to immersion and divergent perceptual abilities. Therefore, no correlational analysis was performed on the results. Future studies should seek to increase the sample size to eliminate this intervening variable and to provide additional insight into measurements.

FUTURE RESEARCH

Realistic Tools Interaction

The desktop version of the hand tracking sensor provides a "tool" feature in which a long slender object, such as a chopstick, is detected and portrayed as a tool within VR. However, the HMD version is in the process of adding this feature. When this feature becomes available, the experiment should be replicated to further account for presence

related to fine-motor tools interaction and visuospatial tasks. The current set of user interactions should be expanded to support more complex visuospatial tasks, such as those encountered when using a ratchet with one hand to thread a screw into a nut being held with the other hand. It is anticipated that a new set of task accelerators and salient cues would be necessary, such as selectively using semitransparent materials on parts involved in the interaction so that the learner may see their virtual hands at all times. Further, it may be necessary to provide a "snapping" and or vector guide line cue that confirms that the learner has properly lined up the ratchet with the screw so that interactions can begin without unnecessary complexity.

Relationship to Situated Cognition and Mental Practice

Situated cognition requires that learning occur within realistic physical contexts. Since virtual hands visualization and interaction are realistically portrayed it is anticipated that they may more closely support the situated cognition approach of learning by doing than do lower-fidelity methods. Future studies should measure if use of virtual hands implementations provides higher cognitive training performance than non-virtual hands implementations.

Research has shown that by imagining physical movement using mental practice that the performance of corresponding physical movement in the real world improves. Virtual hands provide realistic imagery that is highly correlated to kinesthetic and proprioceptive cues associated with actual hand movement. Future studies should evaluate if imitation of tool movements with virtual hands similarly improves tool movements in the real world.

CONCLUSION

In this study equipment maintenance simulation was found to be an exemplary environment in which participants can experience a range of simple to complex cognitive and visuospatial tasks. Participants using virtual hands for equipment maintenance tasks exhibited moderate-high to high levels of presence. Additional study is required to better generalize results and to move towards prescriptive design guidance for the implementation of virtual hands and high presence for ILS. This study should be replicated using larger sample sizes and with expanded demographic coverage for improved internal validity. It is our hope that the results of this study will inform the instructional design and human-computer interaction knowledge bases and stimulate future research of virtual hands design for ILS.

CONSENT AND ACKNOWLEDGEMENTS

APPENDIX A

Presence Questionnaire

Items – Experienced Environment	Subscale
1. How much were you able to control events?	Involvement/Control
2. How responsive was the environment to actions that you initiated (or performed)?	Involvement/Control
3. How natural did your interactions with the environment seem?	Natural
4. How much did the visual aspects of the environment involve you?	Involvement/Control
5. How natural was the mechanism, which controlled movement through the environment?	Natural
6. How compelling was your sense of objects moving through space?	Involvement/Control
7. How much did your experiences in the virtual environment seem consistent with your real world experiences?	Natural
8. Were you able to anticipate what would happen next in response to the actions that you performed?	Involvement/Control
9. How completely were you able to actively survey or search the environment using vision?	Involvement/Control

10. How compelling was your sense of moving around inside the virtual environment?	Involvement/Control
11. How closely were you able to examine objects?	Realism
12. How well could you examine objects from multiple viewpoints?	Realism
13. How involved were you in the virtual environment experience?	Involvement/Control
14. How much delay did you experience between your actions and expected outcomes?	Involvement/Control
15. How quickly did you adjust to the virtual environment experience?	Involvement/Control
16. How proficient in moving and interacting with the virtual environment did you feel at the end of the experience?	Involvement/Control
17. How much did the visual display quality interfere or distract you from performing assigned tasks or required activities?	Interface Quality
18. How much did the control devices interfere with the performance of assigned tasks or with other activities?	Interface Quality
19. How well could you concentrate on the assigned tasks or required activities rather than on the mechanisms used to perform those tasks or activities?	Interface Quality
Items – Included Sounds	**Subscale**
20. How much did the auditory aspects of the environment involve you?	Auditory
21. How well could you identify sounds?	Auditory
22. How well could you localize sounds?	Auditory
Items – Sense of Touch	**Subscale**
23. How well could you actively survey or search the virtual environment using touch?	Haptic
24. How well could you move or manipulate objects in the virtual environment?	Haptic

Note: Presence Questionnaire. (2013). Cyberpsychology Lab of the University of Quebec in Outaouais.

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