Design of a Human Centered Computing (HCC) based Virtual Reality Simulator to train First Responders Involved in the COVID-19 Pandemic

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***Abstract*— The COVID-19 pandemic has placed an overwhelming strain on our Nation's ability to treat patients; the number of patients who need to be tested continues to rise. With nurses also becoming infected, the number of trained professionals who can perform tasks such as testing of patients along with providing care involving hooking up patients to ventilators continues to decrease as well. There is a need to explore the adoption of virtual computer-based training mediums which will enable new nurses and others to be trained in safe and efficient procedures involving patients during this pandemic period. In this paper, the design of a VR-based simulator based on Human-Centered Computing (HCC) principles are discussed. The role of HCC factors such as affordance and cognitive load on the comprehension and scene understanding of nurses during training and the acquisition of knowledge of safety procedures and detailed steps (pertaining to nasal sample collection and use of ventilators on patients) has been studied with the involvement of nurse and nurse trainee participants. Adoption of a participatory design approach involving experts (nurses, doctors involved in covid-19 testing and treatment) has provided a foundational basis for the design of the training environments and assessment activities. Formal information-centric process models of the nasal swabbing procedures and ventilator hookup tasks were created using the engineering Enterprise Modeling Language (eEML). The preliminary results from the assessment activities indicate the positive impact of such HCC based 3D simulators in such training of first responders.**

Keywords*— *COVID-19, Virtual Learning Environment, Immersive technologies, Pandemic, First Responder Training

I. INTRODUCTION

This paper focuses on the design of a Virtual Reality (VR) simulator to help train nurses involved in the testing and treatment of patients affected by the COVID-19 pandemic. This pandemic has placed an overwhelming strain on our Nation's ability to treat patients; the number of patients who need to be tested continues to rise. It is critical that our nation has a larger pool of trained first responders. Currently, there is an urgent need to train such responders (nurses, physician assistants) to perform the testing and ventilator activities in a safe and efficient manner. As it is unsafe to be training nurses face-to-face due to the potential risk of virus contamination, the design of a virtual medium that was user-friendly, efficient, and effective assumed significant. This paper focuses on exploring HCC principles in designing a VR training simulator with two objectives: (i) increase the pool of first responders involved in COVID-19 testing and using ventilators on patients (ii) develop a more effective (and less risky) process to train and prepare such first responders. The design of these training simulators was based on HCC principles including affordance and cognitive load. Such HCC principles have been used in the development of surgical simulators and other environments [23]. In this research, affordance is viewed as the ability of a user or participant to comprehend objects in a target 3D scene and the relationships between these objects so that the trainee can grasp the intricacies of the target training procedures. Cognitive load can be measured using subjective methods such as the NASA TLX test [1], Paas Scale [2], among others. The cognitive load can be measured objectively by using a test called Dual-Task Measures [3-5]. Cognitive load can also be measured by using physiological indices such as pupil dilation, heart rate, muscle activity, among others [6-11].

A preliminary version of this innovative 3D VR simulator has been built using the HTC Vive platform; nurses and hospital staff can wear 3D headsets and complete their training using this simulator. The emergence of low-cost Immersive platforms such as Vive and Oculus Rift have been explored to design VR simulators for medical surgical training contexts [12, 13]; however, this number is very less given the recent emergence of these VR platforms. Such low-cost emerging platforms provide fully immersive capabilities at a lower cost compared to traditional technologies such as CAVE and PowerWall. In [12], a comparison between non-immersive and immersive Vive laparoscopic simulators has been presented.

By training virtually, they reduce their risk of infection while becoming skilled at the various steps involved in the testing and ventilator setup tasks. This simulator will be distributed free of charge to all hospitals nationwide. This simulator is the first of its kind worldwide in helping us handle the outbreak of this pandemic.

The VR-based environments are developed to train first responders in three tasks.

- Pre swabbing task: The focus of this task is equipping of PPE gear in proper order.
- Swabbing task: In this task, the first responders insert the nasopharyngeal swab in the patient's nose, collect the specimen and store it in a test tube safely.
- Post swabbing task: The first responders remove the PPE gear safely and in proper order in this task.

In the paper, the focus is also on understanding and exploring the role of Human-Centered Computing (HCC) factors during the design and development process.

II. Design of the VR based Training Simulator

A Participatory design approach was used in the design of the VR-based simulators where the end-user of the VR-based training would provide input on the design and usage of the VR environment. Participatory Design is a method to involve experts and users of a target system or environment being built [14, 15, 16]. Participatory design has been adopted by several researchers in the field of VR [17-20]. In this project, such an approach is necessary to help in the design process; the design team worked closely with nurses and doctors who were currently interacting with covid-19 patients; this enabled the design team to obtain the perspective of nurses, who would be the end uses of the training environments. Equally important was being able to understand the process intricacies including safety protocols and precautions that nurses follow. The nurse collaborators had dual roles: that of experts who are familiar with such safety and procedural details as well as that of end-users, who would be trained using such a training system.

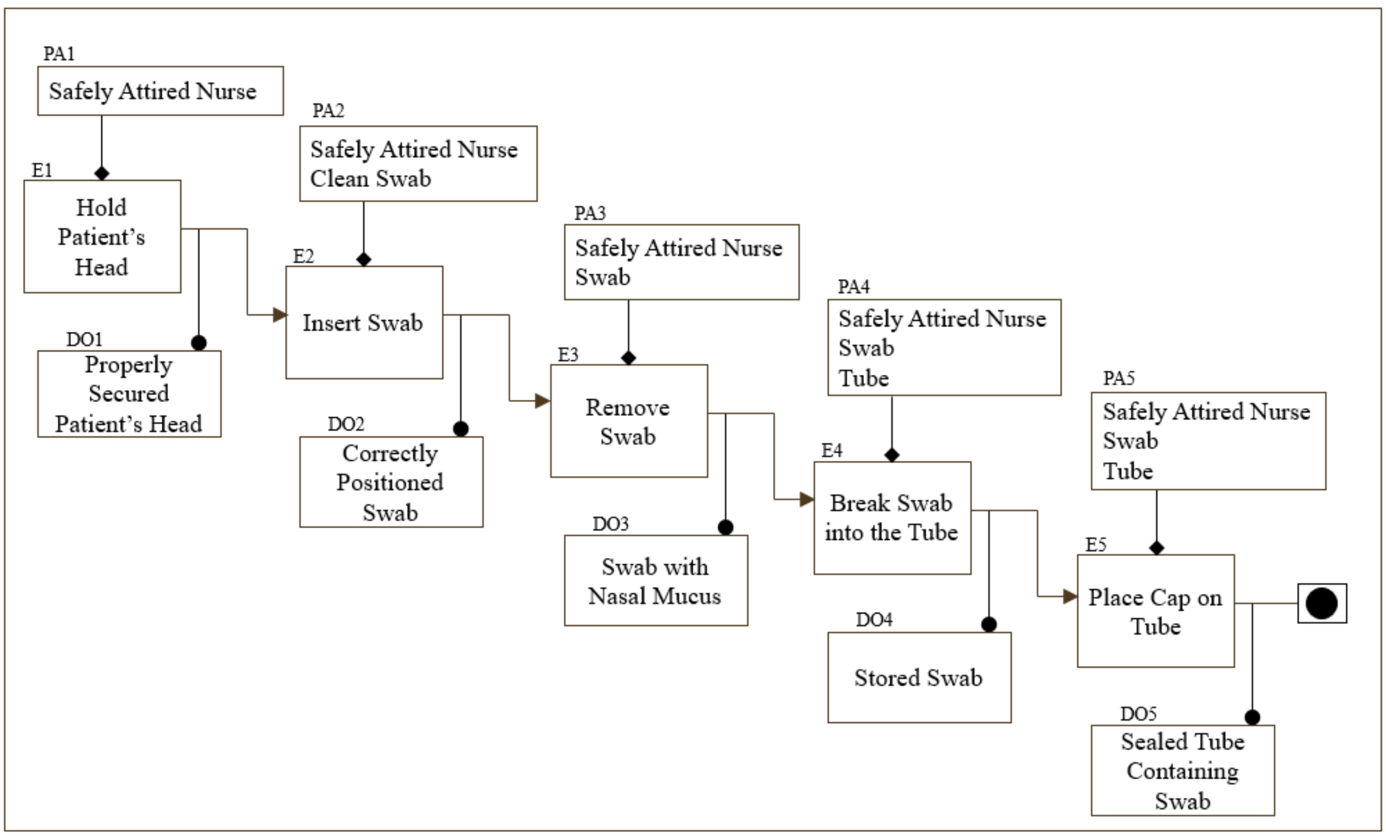

Fig.1. Elided view of the ICPM showing the Swabbing Produre

Communication occurred biweekly during the creation of this information model; modifications and corrections to the information-centric process model were continuous during the initial two-month period. Procedural discussions included details of the various steps, nursing duties, layouts of hospital rooms, presentation of medical equipment, and demonstrations of proper PPE usage, including equipping of gear in order, performing nasopharyngeal swab sampling, and removal of gear.

Based on the suggestion and feedback from nurses and health personnel, information-centric process models (ICPM) based on the engineering Enterprise Modeling Langage (eEML) [25, 26] were created of the target procedures; elided views of one of these models is shown in Fig. 1 for the swabbing task. As it's elided, only the following attributes are shown: the core process step or entity (Es), performing agents (PAs), and decision objects (DOs). Performing agents (PAs) refer to what resources are needed for each step in the procedure; the decision objects (Dos) refer to change in the status after a task or step has been completed; these can be viewed as outcomes (they can be information or physical status changes). Based on the literature review of related work, it appears that this is the first reported adoption of such ICPMs or information flow models used in covid-19 training activities. ICPMs have been explored in other healthcare contexts including the design of immersive surgical training environments [22, 26-28]. In this research initiative, the development goal was to design and build both non-immersive and immersive VR-based training environments for the target training procedures. The focus of discussion is limited to the design of the immersive VR-based training environments. These were created on the Vive immersive platform.

Role of Human-Centered Computing (HCC) Principles in designing User Interfaces

Based on information-centric models, the design of the overall interfaces was accomplished. A hierarchical menu design, beginning from the top-level activities and progressing to lower-level tasks focusing on different aspects to provide assistance or control interfaces was followed. Each of the interactive screens under various user options is designed based on HCC principles. The menu layout, the interactive screens, the types and position of the MR avatar, and other aspects were designed based on affordance and cognitive load. An indirect aspect of importance is a concept proposed that can be termed as the visual density of a 3D scene. In general, the visual density of a 3D scene is the volume occupied by target objectives of a given field of view in a 3D scene as observed by a user or trainee. The relationship between Affordance and visual density is also being studied but the discussion of this aspect is not within the scope of this paper.

Affordance: Affordance is defined as "What the environment offers to the individual" [21], and how it affects learning. If an environment has high affordance, then it has the potential to be a more effective tool for education. Affordance is closely tied to other HCC factors such as cognitive load and visual density. In this project, The concept of dynamic affordance (DA) was proposed which can be defined as the function of comprehension of a scene by a user inside a virtual 3D environment moving along a specific path P (within that target 3D environment) over a fixed period of time (T). DA seeks to throw light on the comprehension and understanding of a target 3D VR environment from various positions and perspectives as a user navigates or traverses along certain paths within that environment

Cognitive Load: Measuring the ***Cognitive Load*** **(CL)** enables the design of training scenarios that will require users to use a lower cognitive load during training. For this project, **CL** is the working memory load burdened on a user using a UI. There is a fundamental relationship between comprehension and the cognitive functioning of a human. The working memory, in general, may vary across individuals or users. If the complexity of a certain task is greater than a user's CL, it negatively affects the learning outcomes resulting in cognitive overload.

In order to understand the effect of cognitive load on users' comprehension, two variants of the training environments (discussed in section III) were developed. The first variant consisted of no distractions whereas the second consisted of several distractions such as red or blue light flashing (Fig. 2) showing emergencies, tables, and equipment falling, among others. The knowledge and skills acquisition in both scenarios were measured in order to study the impact of such cognitive load.

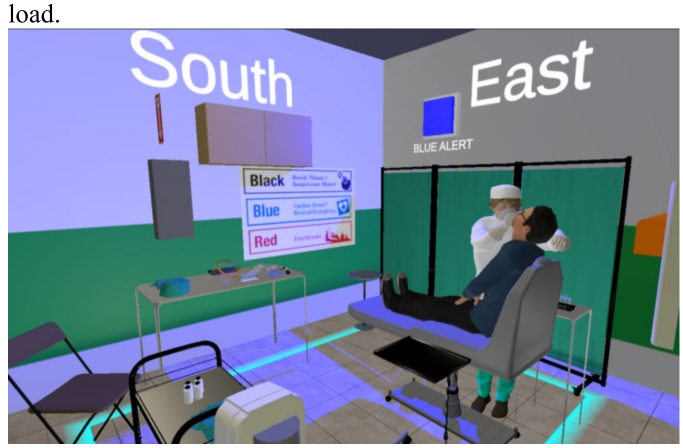

Fig. 2. A view of the environment showing blue light flashing (serving as a distraction)

III. The Creation of the VR Based Training Environments

The VR-based training environments were developed using Unity 3D simulation engine using C# programming language. Solidworks modeling software was used to create the 3D models for the VR environments. The environments were developed for Vive fully immersive platform. A brief description of the three training environments developed for the first responders training focused on the Covid-19 pandemic follows.

A. Pre-Swabbing Training Environment:

The designated "Pre-swab" training environment is divided into three sections in which the users can move freely using the teleportation functionality of the Vive platform. The central section features a 3D model of a nurse standing in front of a table with a large whiteboard behind her, buttons for navigating through steps in the PPE donning procedure or to animate the 3D model, and text describing each step in detail (shown in Fig. 3.). A narration voice plays in the room for each step in the sequence as the user reads the relevant text cues, and the nurse animates to perform each action using PPE gear found on the table in order. The left section features a table with an assortment of PPE items, some of which are required for the COVID-19 procedure, and a mirror sits on the back wall facing the user. The right section features another 3D model of a nurse performing an animated sequence of PPE donning, except the nurse performs one action incorrectly, in this case, it is the lack of a face shield.

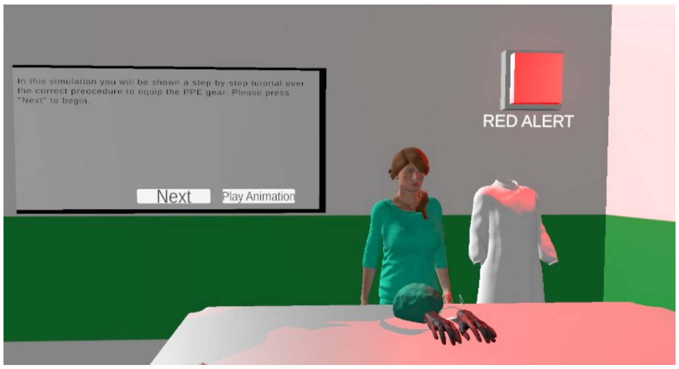

Fig. 3. A view of Pre-Swabbing Training Environment

B. *Swabbing Training Environment*

The Swabbing Training environment consists of an entryway, a hallway that leads forward, and the room on the user's right is labeled "room 1" and the two rooms at the end of the hallway are labeled "room 2" and "room 3". Room 1 features a 3D model of a nurse in full PPE gear and a patient sitting on a hospital bed, with another whiteboard utilizing the same button scheme, text, and audio narration describing the proper nasopharyngeal swab sampling procedure (shown in Fig. 4).

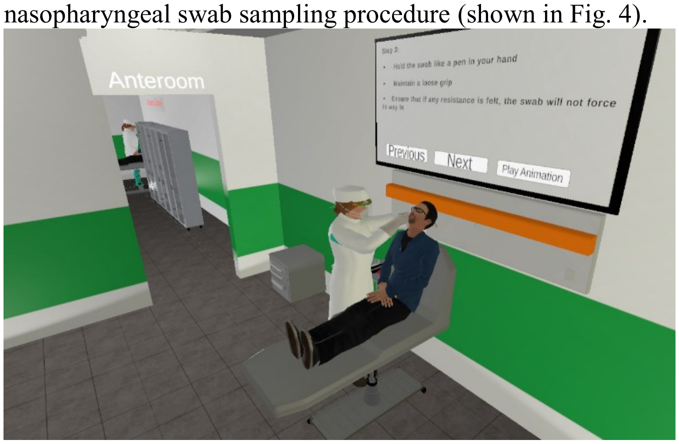

Fig. 4. A view of Swabbing Training Environment showing a nurse inserting the swab inside the patient's nose

This layout can be removed and replaced at will with a simple patient on a hospital bed between two tables, one with a swab and one with a set of test tubes. The user can pick up the swab on the table, grasp and tilt the patient's head back, and insert the swab into the patient's nose, causing green or red dots to appear nearby indicating that the swab is in the correct region of the nasal cavity. Outside of the room is another 3D model of a nurse performing swab sampling on a patient, but one step is done incorrectly, in this case, the nurse does not tilt the patient's head back.

C. *Post Swabbing Environment:*

The Post-swabbing Environment consists of three sections divided by walls to the user's right, each section is labeled "instruction room", "patient care area 1" and "patient care area 2". To the left of the user are another mirror and a trash can for placing PPE gear after it has been removed from the user's virtual body. The instruction room is subdivided by a large grey door, the left of which features a whiteboard and a trash can, the right side features a 3D model of a nurse, and another whiteboard with navigation buttons with the same function as in previous scenes (as shown in Fig. 5). By pressing the buttons, the user reads text and hears audio cues as the 3D model performs proper PPE gear doffing, leaving one section of the room to finish the procedure in the other section. Patient care area 1 shows this 3D nurse model automatically performing these steps in the correct order, while patient care area 2 shows another nurse performing the same sequence with one incorrect step, in this case, it is leaving the patient care area while still wearing a surgical cap.

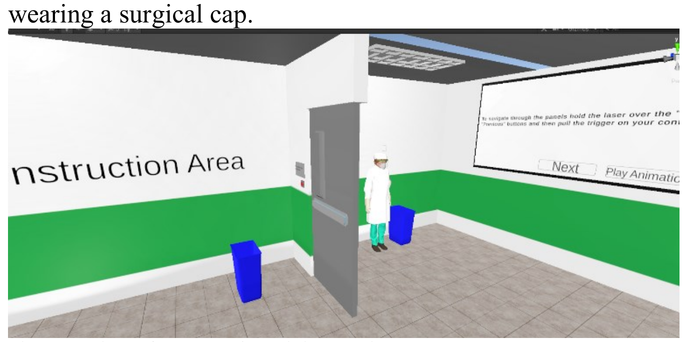

Fig. 5. A view of Post-Swab Training Environment

IV. ASSESSMENT

The assessment activities were conducted with the involvement of nurses at Yavapai Regional Medical Center, Prescott, AZ. The ER nurse manager coordinated the assessment activities involving 30 nurses and nurse trainees. A nurse participant can be seen interacting with the simulator in Fig. 6.

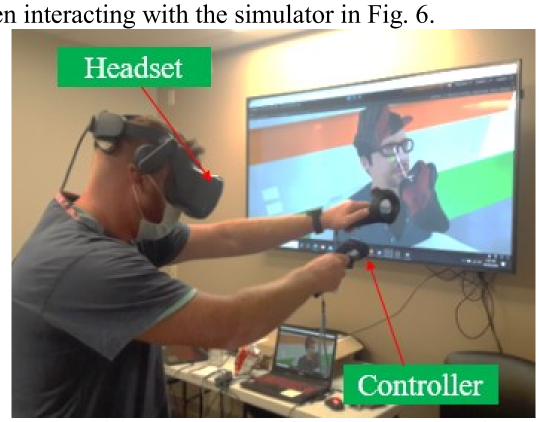

Fig. 6. A nurse participant interacting with the simulator using the HTC Vive immersive platform

A. Assessment of Impact on Knowledge after training

For the knowledge assessment, pre and post-tests were conducted where the participants had to answer questions related to pre-swabbing, swabbing, and post-swabbing tasks. Pre and post-test methods to assess the knowledge improvement has been utilized for other surgical training simulators [22, 26, 29, 30]. After the pre-test, they interacted with the training environments and immersively completed the training modules. Subsequently, they completed the post-test comprising of the same questions as in the pre-test.

As seen in Fig. 7, the average score increased by 14% after interacting with the simulator. A t-test was performed to understand the impact of the simulator on the participants.

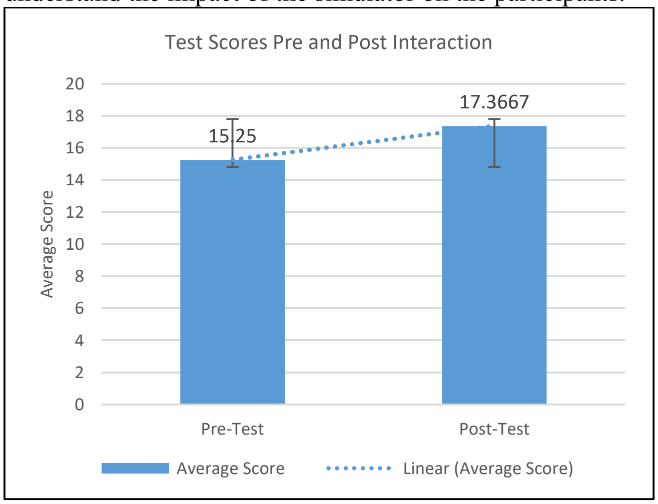

Fig. 7. Average test scores pre and post VLE interaction.

Null Hypothesis:
The interactions with the simulator did not have an impact on the knowledge and understanding of covid-19 procedures by participants.

TABLE I. T-TEST SUMMARY OF PRE AND POST-TEST SCORES

	Distractions	No Distractions
Mean	2.1875	3.0625
Variance	1.9023	0.6836
Stand. Dev.	1.3792	0.8268
N	16	16
| t |	2.1765	
Critical value	2.042	

As shown in Table I, the absolute value of the calculated 't' exceeds the critical value, so the means are significantly different. Based on the results of the t-test, the null hypothesis is rejected.

The conclusion is that the simulation-based training had an impact on the understanding and knowledge of the covid-19 procedure.

B. Assessment of affordance

A related study was performed to see if audio and visual distractions and interruptions similar to those present in a hospital scenario would affect the affordance of a scene experienced by nurse participants. Affordance was measured through tests of scene comprehension, where users would observe a unique scene and answer questions about objects of interest and their perceived affordances. These results were compared to the actual affordances of the objects to create a score.

Cognitive load was measured through heart rate monitoring using a pulse oximeter. During training, participants who underwent training of target procedures with audio/visual distractions and interruptions experienced a 4% higher heart rate than those participants who underwent training without any audio/visual distractions and interruptions.

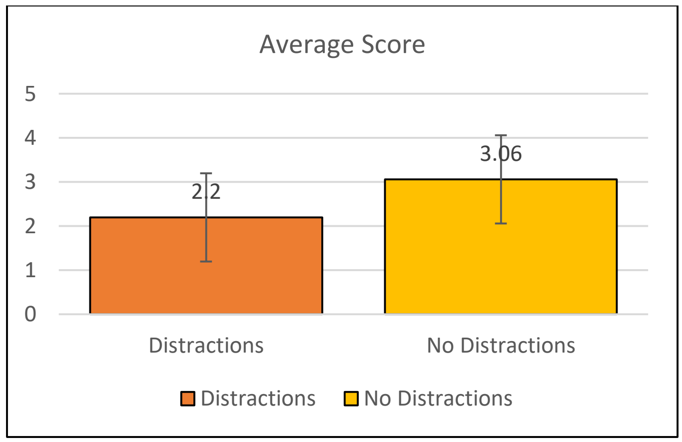

Fig. 8. Results of Affordance studies

As seen in Fig. 8, the average score for the affordance study for the no distraction group is higher than the distraction group. A t-test was performed to assess the statistical significance of the results.

Null Hypothesis:
Distractions and interruptions experienced by participants do not affect the affordance of target scenes.

TABLE II. T-TEST SUMMARY OF AFFORDANCE STUDIES

	Pre-Test	Post-Test
Mean	14.2667	17.3667
Variance	6.5956	13.2989
Stand. Dev.	2.5682	3.6468
N	30	30
| t |	3.9068	
Critical value	2	

As shown in Table II, the absolute value of the calculated 't' exceeds the critical value so the means are significantly different. Based on the results of the t-test, the null hypothesis is rejected and the alternative hypothesis is accepted. The alternative hypothesis is that interruptions and distractions affect affordance and related comprehension of a 3D training scenario by participants.

Additional data has been collected based on the modified NASA TLX criteria on user-friendliness, cognitive effort, frustration, and other attributes. This assessment was conducted on a different pool of 12 experienced nurses from Stillwater Oklahoma (with more than 10 years of experience working in the ER department); 80% of them did not see any difference between an avatar helping them through the training activities as opposed to a voice-over providing instructions and guidance. 90 % rated the user interfaces as training friendly and did not feel the training experience was frustrating (using scales of 1 to 10, with 10 being the highest level of frustration). These 12 nurses were also provided challenge scenarios to study their responses to 3D situations where their understanding of safety procedures and knowledge was assessed. Ten out of the 12 nurses scored 90 / 100 while two scored 80/100.

On another group of 10 nurses (with more than 5 years experience) in Prescott Arizona, the same TLX assessment was conducted. 80% rated the user interface as training-friendly and not frustrating. In challenge scenarios, 57% of nurses scored 90% or higher when performing procedures by interacting with virtual objects, and identifying incorrect procedures. The other 63% of nurses scored 80% or higher.

Based on these initial findings, our preliminary conclusion is that VR training simulators hold the potential to effectively train nurses while ensuring they grasp the intricacies and details of target procedures related to covid-10 contexts. These initial results demonstrated that such Virtual Reality (VR) based environments have the potential to provide an effective and safe alternative to training nurses virtually (rather than physical face-to-face training) without exposing trainees to the potential risk of pandemic infection. This study also investigated the impact of audio/visual distractions and interruptions on participant comprehension; initial analysis indicates it negatively affects the ability of participants to comprehend a target scenario; additional research is needed to study ways to improve the ability of nurses to handle such distractions and interruptions. Research is continuing on expanding the scope of training simulators to other tasks performed by nurses and first responders as well. Training modules aimed at training nurses on how to hook up ventilators to patients diagnosed with covid-19 are also nearing completion.

Future work

Additional assessment studies are planned including a larger population of participants from a wide range of demographics; while experienced nurses performed well under stressful conditions, additional studies are needed to segment the performance of nurses by categories (eg: greater than 10 years, less than 10 years, etc). The performance of nurse trainees and nurses under immersive and non-immersive training environments also needs to be analyzed, which can throw more light on the role of the immersive interfaces in the training experience. Nurses participating in our tests also provided subjective feedback on improvements that could be made in terms of realism and information conveyance.

V. Conclusion

The design of VR-based simulators to help train nurses in the testing and treatment of COVID-19 patients is the focus of discussion in this paper. The role of human-centered computing (HCC) principles in the design and assessment of such VR-based simulators was also discussed. Participatory design approaches were also explored. Assessment activities were conducted and the results were presented which underscored the usefulness of such VR-based simulators in the training of nurses and first responders.

Acknowledgment

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References

[1] Hart, S. G., & Staveland, L. E. (1988). Development of NASA-TLX (Task Load Index): Results of empirical and theoretical research. In Advances in psychology (Vol. 52, pp. 139-183). North-Holland.

[2] Lox, C. L., Jackson, S., Tuholski, S. W., Wasley, D., & Treasure, D. C. (2000). Revisiting the measurement of exercise-induced feeling states: The Physical Activity Affect Scale (PAAS). Measurement in Physical Education and Exercise Science, 4(2), 79-95.

[3] Andersen, S. A. W., Frendø, M., & Sørensen, M. S. (2020). Effects on cognitive load of tutoring in virtual reality simulation training. MedEdPublish, 9.

[4] Andersen, S. A. W., Mikkelsen, P. T., Konge, L., Cayé ‐ Thomasen, P., & Sørensen, M. S. (2016). Cognitive load in distributed and massed practice in virtual reality mastoidectomy simulation. The Laryngoscope, 126(2), E74-E79.

[5] Britt, R. C., Scerbo, M. W., Montano, M., Kennedy, R. A., Prytz, E., & Stefanidis, D. (2015). Intracorporeal suturing: transfer from fundamentals of laparoscopic surgery to cadavers results in substantial increase in mental workload. Surgery, 158(5), 1428-1433.

[6] Menekse Dalveren, G. G., Cagiltay, N. E., Ozcelik, E., & Maras, H. (2018). Insights from pupil size to mental workload of surgical residents: feasibility of an educational computer-based surgical simulation environment (ECE) considering the hand condition. Surgical innovation, 25(6), 616-624.

[7] Zhang, J. Y., Liu, S. L., Feng, Q. M., Gao, J. Q., & Zhang, Q. (2017). Correlative evaluation of mental and physical workload of laparoscopic surgeons based on surface electromyography and eye-tracking signals. Scientific reports, 7(1), 1-7.

[8] Miskovic, D., Rosenthal, R., Zingg, U., Oertli, D., Metzger, U., & Jancke, L. (2008). Randomized controlled trial investigating the effect of music on the virtual reality laparoscopic learning performance of novice surgeons. Surgical endoscopy, 22(11), 2416-2420.

[9] Eyemotion: Classifying facial expressions in VR using eye-tracking cameras. In 2019 IEEE Winter Conference on Applications of Computer Vision (WACV) (pp. 1626-1635). IEEE.

[10] Salminen, J., Nagpal, M., Kwak, H., An, J., Jung, S. G., & Jansen, B. J. (2019, March). Confusion Prediction from Eye-Tracking Data: Experiments with Machine Learning. In Proceedings of the 9th

International Conference on Information Systems and Technologies (pp. 1-9).

[11] Bradley, M. M., Miccoli, L., Escrig, M. A., & Lang, P. J. (2008). The pupil as a measure of emotional arousal and autonomic activation. Psychophysiology, 45(4), 602-607.

[12] Huber, T., Paschold, M., Hansen, C., Wunderling, T., Lang, H. and Kneist, W., 2017. New dimensions in surgical training: immersive virtual reality laparoscopic simulation exhilarates surgical staff. Surgical Endoscopy, pp.1-6.

[13] Harrington, C. M., Kavanagh, D. O., Quinlan, J. F., Ryan, D., Dicker, P., O'Keeffe, D., & Tierney, S. (2018). Development and evaluation of a trauma decision-making simulator in Oculus virtual reality. The American Journal of Surgery, 215(1), 42-47.

[14] Ehn, P., Brattgård, B., Dalholm, E., Davies, R. C., Hägerfors, A., Mitchell, B., and Nilsson, J., 1996, The Envisionment Workshop - from visions to practice, Proceedings of the Participatory Design Conference, MIT, Boston, 1996, pp 141-152.

[15] Harrison, S., 1996, The Participatory Design of Work Space, Proceedings of the Participatory Design Conference, MIT, Boston, 1996, pp 161-162.

[16] Jensen, P. L., 1997, The Scandinavian Approach in Participatory Ergonomics, Proceedings of the 13th Triennial Congress of the International Ergonomics Association, Tampere, Finland, vol 1, pp 13-15.

[17] Sun, X., Wang, Y., De Melo, G., Gai, W., Shi, Y., Zhao, L., ... & Meng, X. (2017, April). Enabling participatory design of 3D virtual scenes on mobile devices. In Proceedings of the 26th International Conference on World Wide Web Companion (pp. 473-482).

[18] Bruno, F., & Muzzupappa, M. (2010). Product interface design: A participatory approach based on virtual reality. International journal of human-computer studies, 68(5), 254-269.

[19] Davies, R. C. (2000). Virtual Reality for the Participatory Design of Work Environments. In Lund University, Sweden, ISBN.

[20] van Leeuwen, J. P., Hermans, K., Jylhä, A., Quanjer, A. J., & Nijman, H. (2018, November). Effectiveness of Virtual Reality in Participatory Urban Planning: A Case Study. In Proceedings of the 4th Media Architecture Biennale Conference (pp. 128-136).

[21] Gibson, James J. "The concept of affordances." Perceiving, acting, and knowing 1 (1977).

[22] Cecil, J., Gupta, A., & Pirela-Cruz, M. (2018). An advanced simulator for orthopedic surgical training. International journal of computer assisted radiology and surgery, 13(2), 305-319.

[23] Gupta, A., Cecil, J., & Pirela-Cruz, M. (2020, August). A Cyber-Human based Integrated Assessment approach for Orthopedic Surgical Training. In 2020 IEEE 8th International Conference on Serious Games and Applications for Health (SeGAH) (pp. 1-8). IEEE.

[24] J. Cecil, “A functional model of fixture design to aid in the design and development of automated fixture design systems’,” J. Manuf. Syst., vol. 21, no. 1, pp. 58–72, Aug. 2002

[25] Cecil, J., Information Centric Engineering (ICE) Frameworks for Advanced Manufacturing Enterprises, Proceedings of Industry Applications and Standard Initiatives for Cooperative Information Systems for Interoperable Infrastructure, OnTheMove Conferences, Sept 10, 2013, Graz, Austria.

[26] Gupta, A., Cecil, J., Pirela-Cruz, M., & Ramanathan, P. (2019). A Virtual Reality Enhanced Cyber-Human Framework for Orthopedic Surgical Training. IEEE Systems Journal.

[27] Cecil, J., Gupta, A., Ramanathan, P., & Pirela-Cruz, M. (2017, April). A distributed collaborative simulation environment for orthopedic surgical training. In 2017 Annual IEEE International Systems Conference (SysCon) (pp. 1-8). IEEE.

[28] Cecil, J., Gupta, A., Pirela-Cruz, M., & Ramanathan, P. (2017). A cyber training framework for orthopedic surgery. Cogent Medicine, 4(1), 1419792.

[29] Gupta, A., Cecil, J., & Pirela-Cruz, M. (2018, August). A Virtual Reality enhanced Cyber Physical Framework to support Simulation based Training of Orthopedic Surgical Procedures. In 2018 IEEE 14th International Conference on Automation Science and Engineering (CASE) (pp. 433-438). IEEE.

[30] Cecil, J., Gupta, A., & Pirela-Cruz, M. (2018, April). Design of VR based orthopedic simulation environments using emerging technologies. In 2018 Annual IEEE International Systems Conference (SysCon) (pp. 1-7). IEEE.