Role of Dynamic Affordance and Cognitive Load in the Design of Extended Reality based Simulation Environments for Surgical Contexts

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ABSTRACT

In this paper, HCI-based design criteria for the Extended Reality (XR) based training environments. XR is an umbrella term used to describe Virtual Reality (VR), Augmented Reality (AR) and Mixed Reality (MR) training environments are presented. The design criteria explored in the paper help lay a foundation for the creation of Human Centric XR environments to train users in an orthopedic surgical procedure. The HCI-based perspective presented in the paper investigates the criteria such as affordance and cognitive load during the design. The paper focuses on the design of XR based environments based on the participatory design approach and information-centric modeling. Further, the paper delineates the implementation of the XR based environments and a set of attributes that guide and influence the content of the environments. Testing and assessment strategy has also been described integrating the design thinking to the assessment and providing insights into the impact of such HCI-based criteria on participants’ acquisition of skills and knowledge during interactions with the XR environments.

Keywords: Human-Computer Interaction (HCI), XR, VR, MR, Orthopedic surgery

Index Terms: Human-centered computing—Human-computer interaction (HCI)—Interaction paradigms—Virtual Reality

1 INTRODUCTION

The use of Extended Reality (XR) based technologies in the design and development of training simulators in fields such as manufacturing, space systems, education, and healthcare have been increasing rapidly [1-4]. As the number of platforms supporting XR such as HoloLens, HTC Vive Pro, and Magic Leap is increasing, the application of such platforms in creating simulators for various surgical domains such as laparoscopic surgery, orthopedic surgery, brain surgery, eye surgery among others, is also rising. The focus of current research is primarily on the software and hardware related issues arising during the development of surgical simulators. Researchers have not aimed at understanding the human centric aspects during the design of XR based environments for surgical context. This paper focuses on understanding the impact of human computer interaction (HCI) based criteria during the design, development, and assessment of an XR based simulator for orthopedic surgical training.

HCI focuses on the design of a computer system, particularly in the interaction between the users and the system. It is a broad field covering various types of systems such as desktops, handheld devices, XR devices, and wearables. Only a few researchers have been researching understanding the HCI centric aspects of the XR platforms and devices [5]. In this paper, two critical HCI criteria have been investigated pertaining to the design of an XR based orthopedic surgical simulator. A brief description of the two HCI based criteria follow.

Affordance
The word affordance was first coined in by psychologist James J. Gibson who defined it as what the environment offers to the individual. In the context of Human-Computer Interaction, the term affordance was defined by Norman as action possibilities that are perceivable readily by an actor.

Cognitive Load
Cognitive load theory categorizes cognitive load into two broad types: intrinsic and extraneous load. Intrinsic load refers to the load imposed by the nature of the topic to be learned. Extraneous load refers to the load imposed by the manner in which the information or instructions are provided to the users. Researchers have developed and utilized a number of objective and subjective methods to measure cognitive load.

2 DESIGN OF HCI BASED XR ENVIRONMENTS FOR SURGICAL TRAINING

The past researchers have only focused on the participatory design approach [6], there is a lack of proper utilization of the participatory design approach during the creation of information models. In this research, the role of creating a formal modeling foundation for the participatory design approach is presented. Such an approach focuses on the utilization of the participatory design approach for the creation of information models to understand the complexities of the surgical procedure. Such an understanding of the complex surgical procedure served as a basis for the creation of information models for the design and development of the XR-based training environments.

For the design of complex XR environments for surgical training, Human-Computer Interaction (HCI) principles can play a pivotal role. HCI (in general) deals with principles underlying the design, evaluation, and implementation of computer systems created for human use. In the context of designing XR based environments for surgical training, such HCI perspectives emphasize the need to establish as early as possible who the appropriate users are and what tasks they are going to perform. Involving the users in the early phase of design can lead to the development of a functional and user-friendly system. Another key aspect is the emphasis on iterative design, which is a cyclic process consisting of four phases: design, test, analyze and repeat. This cycle continues until the users and designers are satisfied with the developed system. In this research, we present a generalized information-centric HCI approach for the design, development, and evaluation of the XR environments.
environments developed for orthopedic surgical training. The focus of the paper is on studying the role of two HCI factors viz. Affordance and Cognitive load during design, development, and evaluation of the training environments. Further, new measures such as dynamic affordance have also been described and implemented in this paper.

2.1.1. Affordance
Affordance can be described as the action possibilities provided to the users in the environment. Dynamic Affordance can be defined as a function of comprehension (C) 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).

2.1.2. Cognitive Load
In order to impose additional cognitive load on the users when they are interacting with the training environments, two stress inducers were introduced in the training environment (described in section 3). The stressors were chosen after consultation with an expert surgeon. The first stressor was the rapid deterioration of the virtual patient’s vitals accompanied by continuous blinking of red light and fast beeping sound. The second stressor was excessive blood loss of the patient (blood hemorrhage) when the user is interacting with the virtual drilling procedure. Two variants of training and challenge scenarios were created; the first with stress inducers and the second without the stress inducers. The focus was on analyzing the effect of such stress inducers on knowledge and skills acquisition in the users.

3 DEVELOPMENT OF XR ENVIRONMENTS FOR SURGICAL TRAINING
The HCI based XR environments were designed for orthopedic surgical training. The orthopedic surgical procedure in focus was condylar plating surgery which is performed to treat the fractures of the femur bone. The VR based environments were developed for Vive Pro immersive platform and the MR based environments were developed for the HoloLens 2 platform.

Figure 1: A view of the VR (left) and MR (right) based training environment for dynamic plate compression

Figure 2: Users interacting with the VR based environment using Vive Pro headset (left) and AR based environment using HoloLens 2 and physical mockup (right)

4 ASSESSMENT RESULTS
The assessment activities focusing on understanding the impact of using XR based training environments were performed at Dignity Regional, Yavapai Regional medical centers, NOC and NWOSU, OK. A total of one hundred and sixty participants were divided into MR and VR groups of eighty for the study. For both MR and VR studies, the eighty participants were divided into two groups consisting of forty participants.

4.1.1. Affordance Results
Group A walked in the center of room and Group B walked in the periphery of the room. Group A (Center Path) scored higher in the questions related to the primary attention area and Group B (Peripheral Path) scored higher in questions related to the secondary attention area. Further, T-tests were performed to confirm the results. For the central path group, the participants scored significantly higher in the questions related to the primary attention area. For the peripheral path group, the participants scored significantly higher in the questions related to the secondary attention area.

4.1.2. Cognitive Load Results
The first group interacted with the environments without any stress inducers (no additional cognitive load) and the second group interacted with the environments with stress inducers (additional cognitive load). The participants who were introduced to stress inducers received lower scores in both skills and knowledge assessment during the interactions with VR based environments. Further, T-tests were performed to confirm the results. For both skills and knowledge assessment, there was a significant difference in the means of the two groups.

5 CONCLUSION
In this paper, an innovative design approach for the design of XR based training environments for orthopedic surgical context was presented. The design approach focuses on throwing light on HCI criteria for the development of effective training environments. HCI factors such as affordance and cognitive load were taken into consideration during the design process of the XR based environments. Assessment studies were also presented and the results of the studies indicate how HCI factors such as affordance and cognitive load affect the users’ comprehension and skills and knowledge acquisition.

REFERENCES