An Investigation into the Role of Affordance in the Design of Extended Reality based Environments for Surgical Training

Avinash Gupta
Center for Cyber-Physical Systems
Dept. of Computer Science
Oklahoma State University
Stillwater, USA
avinash.gupta@okstate.edu

J. Cecil, Ph.D.
Center for Cyber-Physical Systems
Dept. of Computer Science
Oklahoma State University
Stillwater, USA
j.cecil@okstate.edu

Miguel Pirela-Cruz, M.D.
Orthopedics Department
Dignity Regional Medical Center
Chandler, USA
cruzer@zianet.com

Rittika Shamsuddin, Ph.D.
Dept. of Computer Science
Oklahoma State University
Stillwater, USA
r.shamsuddin@okstate.edu

Shelia Kennison, Ph.D.
Psychology department
Oklahoma State University
Stillwater, USA
shelia.kennison@okstate.edu

Christopher Crick
Dept. of Computer Science
Oklahoma State University
Stillwater, USA
chris.crick@okstate.edu

Abstract— **This paper focuses on new types of affordances which can impact the HCI based design of 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. In the context of HCI, the objective is to study the role of affordances in impacting the training outcomes in terms of comprehension and skills acquisition. New affordances are proposed along with a categorization under visual and haptic affordance. The notion of dynamic affordance is also proposed. The impact of these affordances on comprehension and skills acquisition is discussed in the context of a surgical procedure called condylar plating surgery (which is performed to treat the fractures of the femur bone). A genetic algorithm based approach to help in surgical planning is also discussed, which can be integrated with the training activities. The results of Assessment activities on the acquisition of skills and knowledge during interactions with the training environments is also discussed**

Keywords— Human-Centered Computing, Human-Computer Interaction (HCI), Orthopedic Surgical Training, Affordance

I. 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 [1-10]. 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, [11-15] is also rising. The focus of current research is primarily on the software and hardware-related issues arising during the development of the surgical simulator. Researchers have not aimed at understanding the human-centric aspects during the design of XR-based environments for surgical contexts. 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 [16, 17]. In [18], common HCI-based design principles such as affordance, cognitive overhead, user satisfaction, learnability, among others, and their impact on AR system design are discussed. In this paper, different types of affordances involved during the design of an XR-based orthopedic surgical simulator are explored.

The word affordance was first coined in [19] 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 [20].

Gaver delineated affordances as the world's properties, which are defined with respect to how people interact with them [21]. While designing and developing XR-based applications, designers focus on spatial, manipulation, and feedback affordances. Head-mounted XR-based displays provide natural movement of head and body, enabling users to sense the depth of images intuitively, creating a sense of presence. Spatial affordance refers to a person's understanding of the space and the environment around him/her and in what ways he/she can interact with it. Spatial affordance becomes imperative in XR as a person is constantly surrounded by space/environment. A test for objective assessment of judgment and action-based measures to measure perceptual fidelity in AR using HoloLens [22]. A similar study in which HoloLens based AR environment was used to understand the effect of varying wide and deep gaps on users was presented in [23]. During the interactions with AR-based environments for surgical training, a user has to perform complex tasks; however, past researchers focused on how basic tasks such as passing through a door, an aperture, observing gaps affect affordance in virtual and augmented reality [22-26]. There has been a lack of research focusing on spatial affordance during complex tasks. As most of the XR environments, especially in the surgical domain, are designed such that users can perform complex tasks, it is important to understand how spatial affordance affects the users when such tasks are being observed. Other researchers have elaborated on the learning affordance in an XR environment using various subjective and objective questionnaires [27-28]. These affordance questionnaires only serve as basic knowledge-based questions regarding the process without highlighting the importance of understanding the relationship between various objects of interest (OOIs) in the XR environment. In this research, we expand the notion of affordance to include 3D visual, audio, and text-based representations which lend themselves or presents to the user.

The objectives of this paper follow.

- Investigate the role of the HCI design criteria such as affordance during the design of XR-based training environments for surgical context.
- Formulate the categorization of different types of affordances that affect the design of the XR based training environments
- Develop an assessment approach to assess the effect of various affordances on skills and knowledge acquisition of a user during the interactions with the XR-based environment.

The rest of the paper is organized in the following manner. In section 2, the design of the HCI-based XR environments focusing on different types of affordances is presented. The discussion about the development of the XR environments is presented in section 3. In section 4, the results from the assessment activities are elaborated.

II. DESIGN OF HCI BASED XR ENVIRONMENTS FOR SURGICAL TRAINING

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 [49]. 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 developed for orthopedic surgical training. The focus of the paper is on studying the role of different types of affordances involved during the design, development, and evaluation of the training environments. Further, new measures such as dynamic affordance have also been described and implemented in this paper.

In this research, we expand the notion of affordance to include 3D visual, audio, and text-based representations which lend themselves or presents to the user and how the user is able to comprehend the functional relationships between various objects of interest in an XR scene. Further, there is a relationship between cognition and comprehension. In [175], the authors have shown that improving visual cognition can increase comprehension of process models. Further, in this research, an exhaustive categorization of affordance is provided. The classification also includes some of the newly proposed affordances such as dynamic affordance. In static affordance, the user interacting with the environment is stationary and observes the scene from one position. Dynamic affordance is a more encompassing definition of affordance in which the user is in motion and is able to obtain a better understanding of the scene which may come from the price of moving objects, audio, and text-based cues. Figure 1 shows the categorization of the affordance which was proposed in this research. Only two affordances are discussed in this paper for brevity.

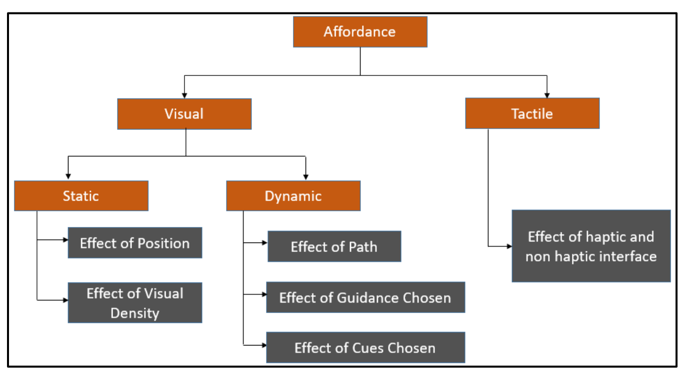

Fig. 1. Categorization of Affordances

A. *Dynamic Affordance – Effect of Path (DA-P)*

Dynamic Affordance (DA–P) can be defined as a 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).

$C = f(P, T)$

$DA\text{-}P <=> C$

For the DA-P related study, a target scene was developed where a drilling procedure was being performed using a drill and a drilling sleeve (drilling is a critical step in condylar plating surgery). The target scene had primary attention and secondary attention area as shown in Figure 2. The users could take a central path or a peripheral path while interacting with the target scene (Figure 2).

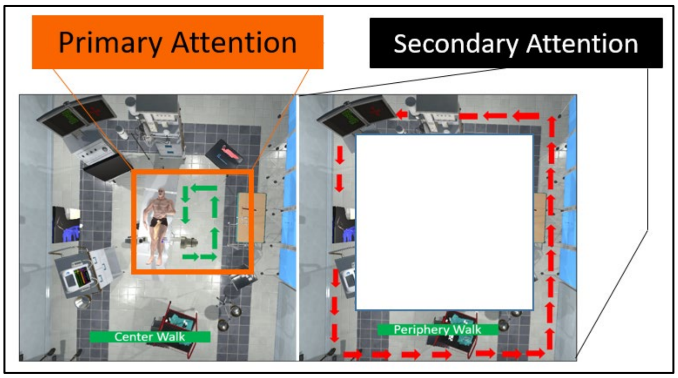

Fig. 2. Primary and Secondary Attention area and the path taken by the users during the interaction

III. 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. The VR and MR environments were developed using the Unity 3D engine. Steam VR tool kit was used for the development of VR environments and Mixed Reality Toolkit (MRTK) was used for the development of MR environments. A total of three VR and three MR training environments were developed for training. Only one of the environments is discussed in this paper for brevity.

The dynamic plate compression environment is the most complex training environment among the three environments. In some critical femur fractures, dynamic plate compression is performed to reduce the bones and complete the treatment. In dynamic plate compression, the two fractured bones are transfixed by exerting dynamic pressure between the bone fragments. Figure 3 shows the views of VR and MR-based training environments developed for dynamic plate compression. During the training, the users learn to complete a complex set of procedures including plate positioning, drilling, and screw insertion. During the training, the users first insert the plate in the correct position and orientation based on the location of the fracture. Secondly, the users fix the plate in the position using clamps. Subsequently, an eccentric drill guide is used to drill holes in the bone. Finally, screws are inserted which compress the bone segment together and transfix them. For the VR-based training, the users interacted with the environment using Vive Pro fully immersive headset. Wireless handheld controllers were used to perform the training activities. For the MR-based training, the users interacted wearing the HoloLens 2 platform. The users interacted with the physical mockup of the training tool and equipment by following the MR-based instructions on the HoloLens 2 headset. The users can be seen interacting with the VR and MR-based training environments in Figure 4.

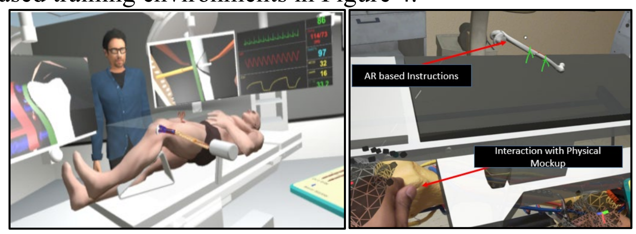

Fig. 3. A view of the VR (left) and MR (right) based training environment for dynamic plate compression

Fig. 4. Users interacting with the VR based environment using Vive Pro headset (left) and MR based environment using HoloLens 2 and physical mockup (right)

B. Genetic Algorithm based Surgical Path Planning

In general, the GA is an evolutionary algorithm that derives its behavior from a metaphor of the processes of evolution in nature. It generates each individual sequence from some encoded form known as a "chromosome" or "genome" [126]. We have used the Genetic Algorithm (GA) to generate the near-optimal positioning of the trays on the two tables in order to decrease the movement of the surgery technician. The table positioning and the position of the trays were included based on the discussions with expert surgeons and surgery technicians. GA pseudocode is shown in Figure 7.

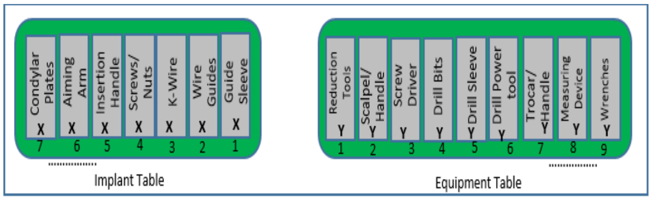

Fig. 5. Implant and Equipment table for the Condylar Plating Surgical Procedure

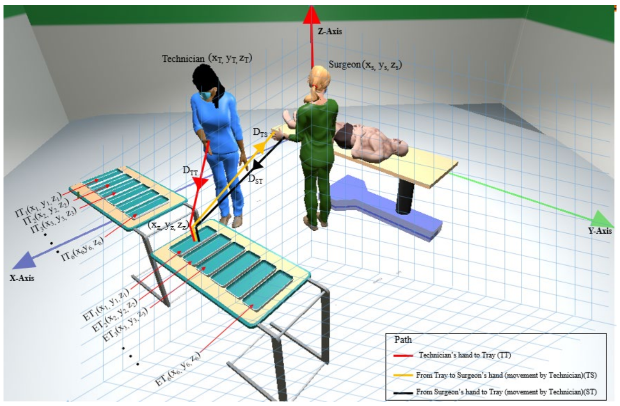

Fig. 6. Layout showing the positions of trays, surgeon, and surgery technician

There are some constraints that have been followed during the development of the optimal positioning of trays using the GA.

- Each implant and equipment are handled to the Main Surgeon in a particular order by the surgery technician.
- The equipment is returned to the table; however, implants stay on the patient (except a few such as Insertion Handle and Aiming Arm).

GENETIC ALGORITHM PSEUDOCODE

1. Generate Initial N Random Population
2. Develop Fitness Function
3. Set Number of Iterations
4. **While** (Current Iteration <= Number of Iterations)
5. Perform Crossover to generate 70% of children
6. Perform Mutation to generate 30% of children
7. **While** (Children Fitness value> Fitness Value)
8. Select Children to form N new parents
9. **If** (Children Fitness value – Fitness Value = Not significant)
10. Stop
11. **End While**

Fig. 7. Pseudocode for Genetic Algorithm

IV. RESULTS AND DISCUSSION

The assessment activities focusing on understanding the impact of using XR-based training environments were performed at four medical centers in Oklahoma, Texas, and Arizona. The expert surgeons involved in the participatory design approach also facilitated the assessment activities. Before the assessment activities, three expert surgeons reviewed the XR-based environments to ensure that the environments replicate the orthopedic surgical process correctly. Subsequently, the surgeons provided feedback that helped in the modification and improvement of the XR-based environments. After the modifications based on the suggestion of expert surgeons, medical personnel (residents, nurses, nursing students, medical students) participated in the assessment. A total of one hundred and sixty participants were involved in the assessment activities.

A. Affordance Study Results – VR Environments

1) Dynamic Affordance – Effect of Path

A total of eighty medical personnel participated in this study to understand the effect of path on the affordance of an environment.

The eighty participants were divided into two groups. The first group interacted with the environment by standing and moving in the center of the room (Group A) and the second group interacted with the environment by moving in the periphery of the room (Group B). A comprehension questionnaire was created focusing on the primary attention area and secondary attention area of the room (shown in Figure 8).

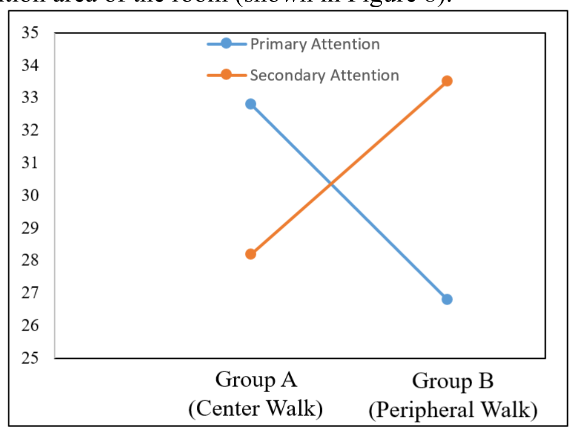

Fig. 8. Result of Dynamic Affordance Experiment – Effect of Path (VR)

The results of the experiment are shown in Figure 8. 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.

Two T-tests were performed to test if there was a significant difference in the means of the two groups (central path and peripheral path). For the central path group, the participants scored significantly higher in the questions related to primary attention area ($M = 32.8$, $SD = 7.73$) than secondary attention area ($M = 28.2$, $SD = 7.70$), $t(78) = 2.7$, $p = 0.004$. For the peripheral path group, the participants scored significantly higher in the questions related to secondary attention area ($M = 33.5$, $SD = 6.44$) than primary attention area ($M = 26.8$, $SD = 5.66$), $t(78) = 4.88$, $p = 0.001$.

2) Dynamic Affordance - Effect of Cues

A total of eighty participants interacted with the environment to understand the impact of cues provided on affordance. The participants were given the freedom to choose their own path during these interactions as well.

The participants interacted with two environments for this experiment. In the first environment, the participants performed the task of inserting the condylar plate (moderate complexity) and in the second environment, they performed the task of dynamic plate compression (high complexity). For both the environments, half the participants performed the tasks following the voice cues, and the other half followed text cues.

The results of the experiment show that the group interacting with voice-based cues scored higher compared to the group interacting with text-based cues. T-tests were performed for both task 1 and task 2. For the moderate complexity task (task 1), the results of the t-test show that there is no significant difference in scores between the group interacting with voice and text cues. However, for the high complexity task (task 2), the group interacting with voice cues scored significantly higher than the group interacting with text cues.

The results showcase that the affordance of a scene is not only dependent on the types of cues provided but also on the complexity of the scene. Due to the high complexity of the scene, the users have to focus more on the surgical procedure being performed. As a result, the users have difficulty following the text cues at the same time. The voice-based cues allow users to dedicate their focus completely to the complex surgical scenario being performed.

B. Affordance Study Results – MR Environments

1) Dynamic Affordance – Effect of Path

A total of forty medical personnel participated in this study to understand the effect of path on the affordance of an MR environment

The forty participants were divided into two groups. The first group interacted with the environment by standing and moving in the center of the room (Group A) and the second group interacted with the environment by moving in the periphery of the room (Group B). A comprehension questionnaire was created focusing on the primary attention area and secondary attention area of the room.

The results of the experiment are shown in Figure 9. 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.

Path/Attention Area	Mean
Center/Primary	34.4
Center/Secondary	27
Peripheral/Primary	29.3
Peripheral/Secondary	36.7

Fig. 9. Result of Dynamic Affordance Experiment – Effect of Path (MR)

Two T-tests were performed to test if there was a significant difference in the means of the two groups (central path and peripheral path). For the central path group, the participants scored significantly higher in the questions related to primary attention area than secondary attention area. For the peripheral path group, the participants scored significantly higher in the questions related to the secondary attention area than the primary attention area.

2) Dynamic Affordance - Effect of Cues

A total of forty participants interacted with the MR environment to understand the impact of cues provided on affordance. The participants were given the freedom to choose their own path during these interactions as well. The experimental design for the study follows.

The participants interacted with two environments for this experiment. In the first environment, the participants performed the task of assembling the plate (low complexity) and in the second environment, they performed the task of dynamic plate compression (high complexity). For both the environments, half the participants performed the tasks following the voice cues, and the other half followed text cues.

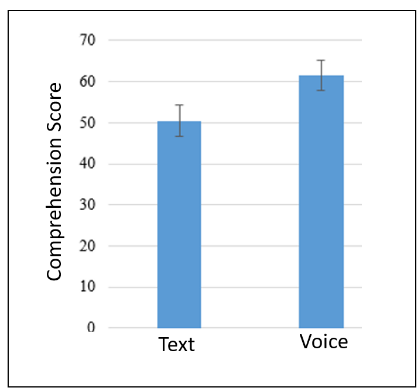

Fig. 10. Result of Dynamic Affordance Experiment – Effect of Cues (MR)

The results of the experiment show that the group interacting with voice-based cues scored higher compared to the group interacting with text-based cues (Figure 10). T-tests were performed for both task 1 and task 2. For the moderate complexity task (task 1), the results of the t-test show that there is no significant difference in scores between the group interacting with voice and text cues. However, for the high complexity task (task 2), the group interacting with voice cues

(M = 61.5, SD = 9.6), scored significantly higher than the group interacting with text cues (M = 50.5, SD = 9.7) , t (38) = 3.59, p =0.05.

In the future, we plan to conduct the assessment activities including a larger population of participants from a wide range of demographics including medical students, residents, budding surgeons, and other ancillary medical staff.

V. CONCLUSION

In this paper, the types of affordances involved in the design of XR-based training environments for the orthopedic surgical context were presented. New affordance criterion such as dynamic affordance was introduced in the paper. Assessment studies were also presented and the results of the studies indicate how different types of affordances affect the users' comprehension and skills and knowledge acquisition.

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