INVESTIGATION OF A HOLISTIC HUMAN-COMPUTER INTERACTION (HCI) FRAMEWORK TO SUPPORT THE DESIGN OF EXTENDED REALITY (XR) BASED TRAINING SIMULATORS

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Abstract: In recent years, the use of Extended Reality (XR) based simulators for training has increased rapidly. In this context, there is a need to explore novel HCI-based approaches to design more effective 3D training environments. A major impediment in this research area is the lack of an HCI-based framework that is holistic and serves as a foundation to integrate the design and assessment of HCI-based attributes such as affordance, cognitive load, and user-friendliness. This research addresses this need by investigating the creation of a holistic framework along with a process for designing, building, and assessing training simulators using such a framework as a foundation. The core elements of the proposed framework include the adoption of participatory design principles, the creation of information-intensive process models of target processes (relevant to the training activities), and design attributes related to affordance and cognitive load. A new attribute related to affordance of 3D scenes is proposed (termed dynamic affordance) and its role in impacting user comprehension in data-rich 3D training environments is studied. The framework is presented for the domain of orthopedic surgery. Rigorous user-involved assessment of the framework and simulation approach has highlighted the positive impact of the HCI-based framework and attributes on the acquisition of skills and knowledge by healthcare users.

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CHAPTER I

INTRODUCTION

1.1 INTRODUCTION

This chapter provides an overview of the various research concepts related to this dissertation research as well as outlines the problem statement and research objectives. The key concepts are discussed in sections 1.2 through 1.6. The problem statement is discussed in section 1.7 followed by the research goals and objectives in section 1.8. Finally, the research contribution is presented in section 1.9.

1.2 OVERVIEW

In recent years, the use of Extended Reality (XR) based simulators for training surgeons and residents in medical universities is becoming more widespread. Researchers have developed XR-based simulators for various surgical fields such as laparoscopic surgery [1, 2, 3], brain surgery [4, 5], eye surgery [6, 7], orthopedic surgery [8-10] among others. This increase is partly due to recent developments in low-cost XR technologies such as immersive (HTC Vive, Oculus), haptic (providing a sense of touch), and Augmented and Mixed reality technologies (Microsoft HoloLens). The American Board of Orthopedic Surgery has also approved the use of simulation-based training in order to improve the surgical skills [11-13] of residents. In this research, the focus is on the creation of a holistic cyber-human framework focusing on the Human-Computer Interaction (HCI) based principles, participatory design-based information-centric principles, and integrated assessment approaches during the design and development of the XR environments for orthopedic surgical training contexts. In this chapter, an overview and definition of various components of the framework are provided.

1.3 NOTION OF A FRAMEWORK

There is no canonical definition for the term ‘framework’. The term framework can have different meanings for different domains and scenarios. The dictionary defines a framework as a basic structure to support or guide the building of something. A software framework, in terms of computer programming, can be defined as an abstraction in which common code which provides general functionality can be modified by user code to provide specific functionality [177]. The framework for complex systems can be defined as the blueprint illustrating the components of the system and the process in which the components interact with each other for the functioning of the system. The framework can also be defined as the platform which serves as a foundation for designing and developing complex applications [157]. In the context of this research, the term framework can be defined as the foundational structure comprising of necessary components such as HCI attributes, participatory design approach, and integrated assessment approach for the creation of effective and human-centric XR-based training environments.

1.4 EXTENDED REALITY (XR) TECHNOLOGIES

Extended Reality (XR) is an umbrella term representing Virtual Reality (VR), Augmented Reality (AR), Mixed Reality (MR), and other related technologies. The definitions of each of the XR technology are presented in the following section.

1.4.1 VIRTUAL REALITY (VR) TECHNOLOGY

Virtual Reality (VR) technology refers to the technology which enables the creation of simulated environments through extensive use of vision, touch, and hearing. VR allows users to immerse and experience an artificial environment in a realistic manner. In the recent decade, there has been a rapid rise in the development of VR technology, especially fully immersive VR technology, which has paved the way for the development of VR systems such as HTC Vive^{TM}, Oculus Rift^{TM}, Playstation VR^{TM}, among others. As such systems are low cost, they have helped VR reach the living room of an average person.

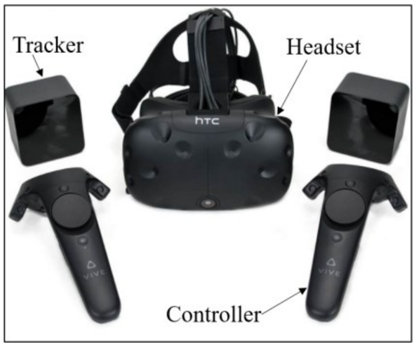


Figure 1.1. Fully-immersive VR technology (HTC Vive^{TM})

1.4.2 MIXED REALITY (MR) TECHNOLOGY

Mixed Reality (MR) technology can be referred to as a merger of the real and virtual world to create a new environment where there is an interaction and co-existence of real and virtual objects. In MR, the user can interact with both the real world and virtual world environment and objects at the same time. Microsoft HoloLens^{TM} and HTC Vive Pro^{TM} are some platforms capable of providing immersive MR experiences.

Figure 1.2. MR technology (Microsoft HoloLens^{TM})

1.4.3 HAPTIC TECHNOLOGY

Haptic-based technology allows a user to experience the sense of touch when interacting with a simulation environment. The primary function of the haptic interface is to give an intuitive 'feel' for various tasks during the interaction with the simulation environment.

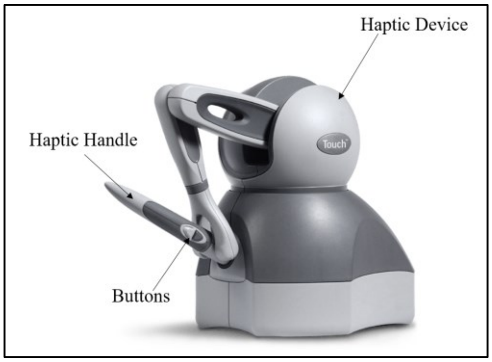


Figure 1.3. Haptic technology (Geomagic Touch^{TM} haptic device)

1.5 HUMAN-COMPUTER INTERACTION (HCI) APPROACH AND PRINCIPLES

HCI is an interdisciplinary area where the focus is on designing computer interfaces with the influence of a human factor. In general, it can be described as principles underlying the design, evaluation, and implementation of computer systems created for human use [14]. National Science Foundation (NSF) and other agencies prefer the term Human-Centered Computing (HCC) to refer to HCI. Other researchers describe HCI as support of interdisciplinary research pertaining to the design and development of novel computing systems to strengthen users' physical, cognitive and social capabilities[15]. HCI-based principles emphasize the need to establish as early as possible who the appropriate users are and what tasks they are going to perform [176]. Involving the users in the early phase of design can lead to the development of a functional and user-friendly system. Another key aspect of HCI proposed by research is the emphasis on iterative design, which is a cyclic process consisting of four phases: design, test, analyze and repeat [178]. This cycle continues until the users and designers are satisfied with the developed system. HCI can play a critical role during the design of XR-based training environments, which is the focus of this Ph.D. research. HCI can influence the way in which information, data, audio, text, and video cues can be displayed so that the users can effectively and efficiently understand and comprehend the training process at the heart of which is the 3D content and user interfaces. An effective HCI-based design will enhance the training process by impacting users' cognitive and comprehensive abilities. Some of the HCI-based attributes that have been investigated in this research include cognitive load, affordance, and visual density. A brief description of these terms follows. A more elaborate discussion of HCI concepts and principles investigated in this research can be found in chapter 4.

1.5.1 COGNITIVE LOAD

Cognitive load refers to the working memory load utilized by a user when performing a particular task [16]. In learning complex tasks such as flying airplanes and performing surgeries, the cognitive load becomes a crucial factor. The working memory is limited and differs from one person to another. If the complexity of a certain task is greater than the working memory of a person, the learning is negatively affected and the person is cognitively overloaded [73]. In this research, the focus is on understanding the impact of various types of cognitive load on users' skills and knowledge acquisition. The various types of cognitive load have been described in chapter 4, section 3.3. The impact of such cognitive load on users during the interaction with the XR-based training environments is presented in chapter 7.

1.5.2 AFFORDANCE

Affordance delineates the possible uses of an object/environment or defines how the object can be used or how the environment can be interacted with [17]. Affordance is not a physical property of the environment but the relationship between the user and the environment. It is a subjective experience of the user with the environment. For example, Figure 1.3. shows a staircase whose affordance needs to be determined. For some users, the affordance when they see the image of the staircase is that it provides a way to go up and down from one-floor level to the next; while for some other users, the staircase provides a place to sit and relax. In this research, we have identified and adopted new measures such as dynamic affordance. Further explanation of dynamic affordance and other related concepts are presented in chapter 4, section 3.

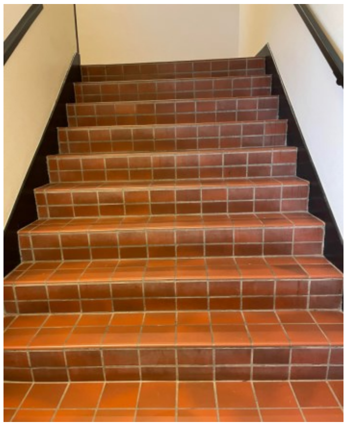


Figure 1.4. View of a staircase and Affordance: some users may see this image of a staircase and understand that it can functionally provide a way to go from one floor level to another; to other users, the same staircase can functionally serve as a place to sit and relax

1.5.3 VISUAL DENSITY

Visual density for 2D user interfaces can be defined as the vertical and horizontal compactness of the components in the UI [18]. Visual density for 3D interfaces can be defined as the number of objects per cubic unit of the 3D environment. In this research, the focus is on understanding the impact of training environments with varying levels of visual density on the users' comprehension, skills, and knowledge acquisition. An elaborated discussion of visual density has been provided in chapter 4, section 3.

1.6 PARTICIPATORY DESIGN

Participatory design refers to the process of the target audience for whom a system is being designed to be involved in the design process [19, 20]. It is a democratic design process for the design of social and technological systems based on the argument that users should be involved in the design and all stakeholders should have input during the design process [51]. In this research, the role of information modeling methods to support capturing the knowledge of target processes through participatory design activities has been investigated. The participatory design approach is explained in more detail in chapter 3, section 3.

1.7 VOIDS AND PROBLEM STATEMENT

A thorough and careful review of the related literature has been conducted and can be found in chapter 2. Based on the completed literature review, some specific voids have been identified:

1. There is a lack of research involving the investigation of holistic or comprehensive frameworks proposed for the design of the XR-based training environments; past research has not recognized the need to have such holistic frameworks which are needed to design efficient, effective, and training friendly simulation-based environments. There is a need to propose a framework which can address various key elements that take into consideration HCI principles, support participatory design as well as seek to integrate the design-assessment activities[137-140].
2. In the area of participatory design [53-57], there is a lack of a structured process to support the acquisition of knowledge of a target process of interest in which users or participants will be trained. There is a need to address this key void, which will provide a formal foundation to represent the various functional relationships of a target process of interest.
3. Within the realm of HCI-based design, there is a need to focus more on additional aspects of affordance made possible due to emerging technologies that support additional levels of immersion and user experiences. There is a need to delve deeper into the notion of affordance and propose new concepts that go beyond static affordance; past research

has not also examined closely the role of haptic affordance as well as the role of Mixed Reality mediums and how they impact user affordance and training experiences.

4. A major void relates to assessment approaches related to studying the impact of such 3D simulators on knowledge and skills acquisition. There is a need to propose integrated approaches which link the emphasis on HCI-based design to the degree of knowledge and skills transfer. Such an integrated approach will enable greater cohesion while at the same time helping identify unique design attributes in the 3D training environments which can help participants and users grasp complexities in the training content. Past researchers have not focused on integrated assessment approaches leading to unaddressed issues related to designing the environment and assessing the effectiveness of the learning outcomes.

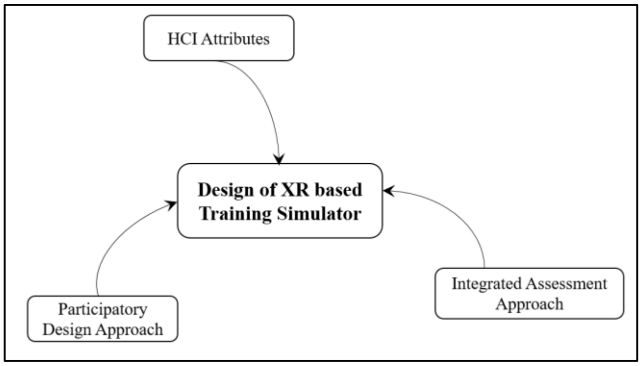


Figure 1.5. Components for the creation of effective human-centric XR based training environments

1.8 RESEARCH GOAL AND OBJECTIVES

The overall goal of the proposed research is to explore the creation of a novel holistic HCI-based framework to support the design, development, and assessment of XR-based training simulators. The process context for this dissertation research is in the domain of orthopedic surgical training. Interaction with expert surgeons, nurses, and healthcare professionals is a key part of the participatory design approach.

In order to achieve the overall goal, the following objectives are identified:

1. Investigate the design of HCI attributes and the role of such attributes (affordance, visual density, and cognitive load) in the creation of novel effective human-centric XR-based training environments.
2. Explore the role of building information models to support the capture of the knowledge acquired of the target surgical procedures during the participatory interactions with expert surgeons, nurses, and residents.
3. Design a comprehensive approach to facilitate assessing the impact of various HCI-based attributes on knowledge and skills transfers in XR-based training environments.
4. Demonstrate the feasibility of the proposed approaches (from 1, 2, and 3) by creating various simulation-based training modules, experiments, and user experiences using emerging software tools and platforms
5. Interact with healthcare users and participants and collect user performance data in terms of skills, and knowledge acquisition and summarize key findings which will enable the creation of more effective content involving 3D-based training simulators.

1.9 RESEARCH CONTRIBUTION

The primary contribution of this research is the creation of a novel and holistic HCI-based framework for the design of XR-based environments for surgical training. Such a framework will enable designers of 3D simulation-based training environments to design user-friendly, human-centric training environments which will facilitate more effective and enriched user experiences that will translate into better-trained workers. One of the unique aspects of this research was the involvement of the expert surgeons who are the training experts in the target process of interest, which was in orthopedic surgery. For the first time ever, an information-centric process model of the entire target surgical procedure has been created which identifies the core steps of the surgical procedure along with the information/physical inputs, constraints, and other functional elements to help obtain a greater understanding of the complex surgical procedure. The participatory activities not only involved these experts but also nurses who support the surgical activities and the end-users who are residents (to be trained) using the 3D XR simulators.

In the context of the HCI-based design activities, new concepts have been proposed including the notion of dynamic affordance along with additional demarcation of concepts in affordance such as visual and haptic affordance. Another key contribution is the study of the relationships of these existing and newly proposed attributes to each other as well their impact on a user's comprehension and understanding of 3D training content. Finally, an elaborate assessment approach has been proposed and validated which involves linking the impact of specific HCI-based design attributes to the improvement of knowledge, understanding, and skills transfer during training of participants.

1.10 CONCLUSION

In this chapter, a brief overview of the HCI-based framework for the creation of XR-based surgical training environments was presented. Further, the definition of the components related to the creation of the framework was also discussed. In the later part of the chapter, the voids in the current research were elaborated which lead to the creation of the problem statement. Finally, the objectives of the research were identified and delineated. In chapter 2, a detailed literature review supporting the voids and problem statement illustrated in this chapter have been provided.

CHAPTER II

RELATED WORK

2.1 INTRODUCTION

In this chapter, an exhaustive review of the current literature related to research is presented. In section 2.2, the review of XR-based simulators in surgical training is provided followed by the review of XR-based simulators in orthopedic surgical training in section 2.3. In section 2.4, a review of XR framework proposed by other researchers is discussed. The review of the participatory design approach is presented in section 2.5. In section 2.6, the related work pertaining to information modeling is included. The current work in the HCI domain is discussed in section 2.7. A review of assessment methods is provided in section 2.8. In section 2.9, a review of current networking approaches in the XR domain is included. In section 2.10, the voids in the current research are presented along with the showcasing current research in the XR-based framework and the work being conducted in this research.

2.2 XR BASED SIMULATORS FOR SURGICAL TRAINING

Jefferson et al. [27] presented initial outcomes of using an immersive VR-based preoperative planning tool for laparoscopic donor nephrectomy. The author stated that it was challenging to understand more than 2500 CT images hence they developed 3D models using 3D slicer which allowed an interactive and comprehensive anatomy when viewed through an immersive headset.

The CT images of seven patients were used for a study in which two surgeons assessed the preoperative understanding using CT alone and CT on the immersive headset. The results from the study indicated that immersive models enhanced the surgeons' understanding of the patient's arterial and venous anatomy. Moreover, the surgeons' overall confidence regarding the operation improved while interacting with the 3D image on the immersive headset.

Luciano et al. [28] presented a periodontal simulator which allowed the trainees to perform both diagnosis and treatment of periodontal diseases by visualizing the 3D virtual human mouth. They stated that dentists required tactile sensation to perform diagnostic and surgical procedures for which haptic device was used which allowed dentists to touch the surface of teeth, calculi, and gingiva using virtual dental instruments. The mode of interaction was via a stereoscopic display and a SensAble Phantom Haptic device. The graphics rendering was developed using Coin and General Haptic Open Software Toolkit (GHOST) was used for the haptic rendering. A preliminary evaluation of the simulator was conducted where the trainees were asked to rate the simulator on criteria such as ease of use, engagement among others. The results from the evaluation were positive and the vast majority of users adapted to the system easily and found it easy to use and navigate.

Shi et al.[29] stated that haptic-related computation plays the most important role in the successful implementation of any virtual reality system. They discussed haptic-related computation for virtual liver surgery which included mechanism of haptic computation, liver cutting area delineation, and liver parenchyma splitting simulation. For the delineation, they adopted an improved Dijkstra-based algorithm to compute the geodesic on triangle mesh of the virtual liver. For the soft body deformation and splitting simulation, two liver models are aligned which looks as if it has not been cut at the beginning. Only when a virtual electrotome is used to cut the liver, the two models separate. A haptic interface which consisted of the Phantom Omni haptic device was used to manipulate the surgical equipment such as the virtual electrotome.

Tolsdorff et al. [30] developed a haptic-based simulator for sinus surgery. Three-dimensional Voxel model of the human skull was created from the CT scan data by multi-step threshold segmentation of boney structures. Nerves, arteries, mucosa, etc. were added manually later. Low-cost Phantom Omni haptic device was used to interact with the simulator. An important aspect of the simulator was the tissue removal process which was achieved by eliminating the voxels of the cut-out region. Ray casting algorithm was used to smoothen out and round of edges of the cut portion. Haptic rendering and visualization are also represented at the sub-voxel level.

Choi et al. [31] presented a virtual cataract surgery simulator to perform phacoemulsification procedures. The focus of the simulator is training in cornea incision, capsulorhexis, and phaco-sculpting These processes were simulated using efficient tissue deformation and surface and volume cutting algorithms. Phantom Omni haptic device was used as the user interface to interact with the simulator. The simulator was developed using OpenGL and OpenHaptics. The authors state that the simulator can serve as a training tool to supplement current training methods.

Echegaray et al. [32] developed a haptic-based brain surgery simulator. The simulator used CT images for 3D visualization of the skull and MRI images were used to create the volume of the brain.

The simulator used a nonlinear FEM-based approach to simulation the deformation of tissues during the interaction. The Phantom Omni haptic device was used for interaction with the simulator; the haptic rendering was achieved using the mass-spring model which provided realistic and stable sensation to the user. The authors state that additional improvement is required in terms of haptic, visualization, and volume cutting methods.

A mixed-reality simulator to training in Nasal Endoscopy is presented was presented by Barber et al. [33]. The mixed reality-based approach used HTC Vive, 3D printed model, and Vive trackers. Vive trackers were placed on the 3D printed skull and the endoscope through which the virtual skull and virtual endoscope were synced. Using this approach, the users could interact with the virtual object in the Vive based 3D environment and at the same time could feel haptic sensation from the real object as well.

Huber et al. [34] have compared a non-immersive laparoscopic simulator with a fully immersive Vive laparoscopic simulator. 10 members of the surgical department participated in the comparison task. The participants performed three tasks which were peg transfer, fine dissection, and cholecystectomy. The results show that participants show a high level of exhilaration when using the Vive simulator due to the high level of immersion.

Wijewickrema et al. [35] have discussed the design of a haptic Cochlear implant surgery training module. They have also evaluated the module through pre and post-test. The evaluation revealed that the participants found concurrent verbal and visual cues helpful.

2.3 XR BASED SIMULATORS IN ORTHOPEDIC SURGICAL TRAINING

A Mixed Reality-based surgical navigation system for orthopedic surgical navigation has been discussed by Wu et al. [36]. The MR-based navigation system consists of Hololens display, a magnetic launcher, a passenger sensor, and a processer. The MR-based system is useful in providing real-time 3D visualization. Using the MR-based system, the 3D reconstructed virtual model generated using CT scan or MRI can be integrated with the body of the patient which can be helpful in guiding the operating procedure. Such a system provides additional visual information related to the internal organ of the patient which is not visible to the naked eye. MR-based navigation system has several advantages over the conventional image-guided surgical system such as intuitive and detailed imaging information, less time spent and mental load, low risk of errors among others.

Mohamed et al. [37] discussed the recent trends in the field of orthopedic simulation and the challenges associated with it. They have listed the challenges below-

- Large range of 3D objects (220 bones)
- Large number of types of fractures
- Problem of simulation of bones' properties
- Huge range of sizes and anatomical features

A virtual bone drilling tool for dental surgery has been discussed by Kim et al. [38]. The simulation method is able to handle arbitrarily shaped tools with multiple contact points. In this method, a signed distance field represents the tool, and voxels surrounded by a point shell represent the bone. The point shell is updated when the bone element is chipped reflecting the deformation of bone in real-time, while the collision detection and the reflected force are efficiently and accurately computed from the distance field encoded in the tool.

Tsai et al. [39] presented a virtual simulator that was capable of performing various surgical procedures. This was one of the earlier papers about virtual orthopedic surgery. Their simulator could perform arthroplasty, corrective or open osteotomy, fusion, open reduction, and amputation. Their system architecture consisted of an interface module, data conversion module, isosurface construction and rendering module, and simulation module. The software was developed using C++ and using the OpenGL libraries to render the isosurfaces. The user wore eyeglasses to observe stereographic images. A surgical instrument attached with a 6D dimensional tracker was used to interact with the simulator. A study was also conducted and the results suggested that the simulator can be used as a useful learning tool and can be used for planning and rehearsal of operations.

Vankipuram et al. [40] described a virtual drilling simulator which provided visiohaptic interaction with virtual bones. The Virtual bones for the simulator were created from CT scans and transformed into a bone voxel model. A collision detection algorithm was used to determine the voxel-tool interaction called collision detection. The process by which voxels were removed by simulation drilling was known as erosion logic. For the haptic interface, they used the

Phantom device which was modified with Synthes surgical drill. A major contribution of the paper is the force-related calculation for the haptic-based bone drilling during simulation.

Sabri et al. [41] developed a serious multiplayer game to train total knee arthroplasty (TKA) to residents. They stated that the serious game provided an active and critical learning approach for residents. This game behaved like a typical first-person shooter game where the world is viewed from the gamer's viewpoint. They concluded that their gameplay approach would provide residents with a better understanding of the surgical procedure and would make them better prepared for the actual surgery.

Citak et al. [42] proposed a novel virtual fracture reduction tool for acetabular fracture. They studied the effect of this tool on accuracy and time taken for reduction. For better visualization and manipulation, they included 3D glasses and a rollerball-type input device with six degrees of freedom. They tested their tool and results showed a significant difference in translational malreduction and decrease in time taken but no difference in angular reduction error.

Zhu et al. [43] discussed a novel simulation framework to develop real-time based minimally invasive surgery (MIS) simulators. Their model was based on distinct physics points rather than a mesh particle system. For the simulation of elasto-mechanical properties, they have used Smoothed Hydrodynamics (SPH). To handle contacts and collisions, a uniform grid method was used. External forces are usually added on one point in the point-based system which causes various inconsistencies; they used pressure masks for smooth force distribution to solve such problems occurring due to external forces.

Assassi et al. [44] described a process for musculoskeletal disorders simulation. According to the paper, the diagnosis strictly depended upon patients' feedback which may not be accurate all the time. They stated that computer graphics offer a suitable avenue for pre-operative planning and post-operative rehabilitation. A motion tracking system, which is widely used for animation, was used for analyzing the joint movement. Finite element method, which is a very popular method in engineering, was used to simulate the physical properties of bones.

Shi et al. [45] discussed the role of a visuo-haptic training simulator in the education and training of residents. The simulator was developed for a widely practiced surgery in the field of spine surgery known as pedicle screw placement. In spine surgery, it is crucial to position the screw correctly as neural structures are close to the bony pedicle. A study was conducted to assess the role of such a simulator in the training of the medical residents. In the study, the residents (no. = 5) first trained on the VR simulator. Subsequently, they perform the same steps on a human cadaveric spine specimen. Finally, the positions of the pedicle screws were evaluated and compared to a control group (no. = 5) which did not interact with the simulator and only learned the steps through the traditional teaching method. The results show a significant difference in screw penetration rates, screw placement accuracy, acceptable rates of screws, and average screw penetration distance between the training and control group. This study shows that the VR simulator can be a useful method to train medical residents before surgery.

Sugand et al. [46] have studied the effect of a VR simulator in the training of dynamic hip screw procedure. The procedure consisted of 7 steps. 52 naïve surgical trainees were randomly assigned into two groups; the training group attempted the procedure 5 times whereas the control group attempted it only a single time. Total procedural time (sec), fluoroscopy time (sec), number of radiographs (n), tip-apex distance (TAD; mm), attempts at guidewire insertion (n), and probability of cut-out (%) were the objective training matrices. The results showed that the training group was 68% quicker than the control group, used 75% less fluoroscopy, took 66% fewer radiographs, had 82% fewer retries at guide-wire insertion, achieved a reduced TAD (by 41%), had a lower probability of cut-out (by 85%), and obtained an increased global score (by 63%) which suggested that the VR training simulator has a positive impact on DHS training.

A VR-based hip replacement surgery simulator is discussed by Kaluschke et al. [47]. Milling is an important aspect of this surgery. However, the surgeon cannot see where or how he/she mills, but only feels the force of the reamer. In order to construct a realistic simulator, high forces are required to mimic the milling forces. The authors for this purpose have used an industrial robotic arm for force feedback. The robotic arm was not built for haptic feedback hence novel control and haptic rendering algorithm were implemented on it. The haptic rendering algorithm computes collisions of the reamer with the hip and generates forces and torques, including an appropriate friction model. The haptic control mechanism controls the robot. It receives the forces and torques from the haptic rendering algorithm and transfers them into a stable configuration of the industrial robotic arm.

A Mixed Reality Surgical Simulator for Hip Arthroplasty training is presented Turini et al. [48]. The overall system, main phases of design, and development of the HoloLens based simulator are discussed. The system combines patient-specific replica, AR features, and audio technology. The CT scan of the required bones was used for the creation of virtual models and 3D printed physical content. The Arthroplasty Virtual simulator provides two configurations (1) visualization of bones, pelvis, and preoperative planning and (2) complete virtual content with hidden muscle. Students were asked to assess the simulator using a Likert Questionnaire form. Positive feedback was provided for Head Tracking, Gesture, voice interaction, and spatial sound. However, a neutral opinion was expressed about the ease of aligning surgical instruments with AR view finder.

El-Hariri et al. [49] presented a method to create 3D volume to align pre-operative data to intra-operative information from optically tracked ultrasound and CT images. The AR-enhanced scene can be visualized using Microsoft's HoloLens. A study to demonstrate the capability of the method has been conducted using a foam pelvis phantom by comparing the location of fiducial markers in the real and virtual spaces. The RMS errors for the x, y, and z axes were 3.22 mm, 22.46 mm, and 28.30 mm respectively.

Gamification as a learning strategy is used by Gonzalez et al. [50] to enhance medical students' skills in knee cruciate ligament surgery. The simulator is developed for the HTC Vive platform. The simulator first shows a tutorial related to the steps to be followed. Subsequently, the users train using the simulator. A total of 30 users completed the learning with and without the tutorial. The results were taken for criteria such as score, time, precision, error, and sequence. Out of 950 points, 20 students received a score of 720, and 10 received a score of 700. The results show that the knee surgery simulator not only helped train in the surgical procedure but also motivated them to improve their medical skills.

Schlueter-Brust et al. [185] presented an AR based simulator for reversed shoulder arthroplasty. The simulator was developed using Microsoft HoloLens 2 and was designed for positioning of K-wire for the glenoid component. A proof-of-concept study was also conducted in which the discrepancy between planned and achieved glenoid entry point was 3mm and k-wire orientation mean angular error was 5 degrees.

Apart from the surgical domain, XR-based simulators have been developed for other domains such as manufacturing [136-142], space systems [143-150], education [151-155], among others.

2.4 XR FRAMEWORK

Pfeiffer et al. [137] proposed a VR framework for surgical application which allowed handling of patient data in a VR environment. The focus was on patient data handling, visualization, and assessment. The framework supported the organization of data into workplaces and allowed users to control, manipulate and enhance the data. 77 clinical personnel interacted for the evaluation of the framework. The majority of participants stated that it was easier to understand and comprehend complex surgical scenarios using the framework.

Fiederer et al. [138] developed a framework for VR-based neurosurgery based on open source tools. The focus was on constructing 3D models from MRI and CT data using open source software such as Freesurfer, 3D Slicer. Further, they developed a VR environment using Unity 3D. Two surgeons compared the 3D models with the 2D images and were surprised by the accuracy, immersion, and speed of information assimilation using the 3D models.

Xiao et al. [139] developed a physics-based framework for Neonatal Endotracheal Intubation. The framework was fully immersive which utilized Vive Pro and Geomagic Haptic touch platform. A validation study was conducted using a commercial AR simulator in which skills assessment and subjective surveys were performed.

Karabiyik et al. [140] proposed a VR framework for first responder and forensic investigator training. The framework included various functions assigned to virtual objects which were customizable. The framework supported training for various procedures, pipelines, and task execution sequences. After the training, the users performed challenge scenarios where they had to collect as much evidence as possible. The evaluation included: missing evidence, task execution sequence, and task completion time. The framework supported multiple platforms such as Vive, Oculus Rift, and Samsung Odyssey.

Allard et al. [160] developed a framework called Open Source Framework for Medical Simulation (SOFA) allowed users to create complex simulations by merging new algorithms with algorithms already available in SOFA, modifying parameters such as deformation, surface representation, and collision by simply editing the XML files, building complex scenes using simple ones, simulating dynamics of interacting objects and reusing and comparing available models in the SOFA framework. In the SOFA framework, any behavior model can be an amalgamation of a visual model, collision model, a haptic model, and other mapping models. The objective of the SOFA framework is to provide a common software framework for the medical community, enabling component sharing, promoting collaboration, enabling validation, and helping standardize the anatomical and biomechanical datasets.

2.5 PARTICIPATORY DESIGN

Participatory Design is a method to involve the people who are going to be affected to have their input during the design process [19, 20]. It is a democratic design process for the design of social and technological systems based on the argument that users should be involved in the design and all stakeholders should have input during the design process [51]. The participatory design method was first used in Scandinavia [52]. Participatory design has been utilized by several researchers in the field of VR [53-57].

Participatory design for the creation of 3D virtual scenes for applications such as virtual museums has been used in [55]. The users can create 3D virtual scenes using a laptop-style device with dual touch screens. Such a system facilitates designers to flexibly and rapidly create virtual scenes based on users' input. A study was also conducted with 25 participants and the results indicated that the system has high usability and improves the efficiency of the design process.

In [54], a study was presented to evaluate the feasibility and the efficacy of the participatory design approach to evaluate the usability of virtual product interfaces for products such as microwave and electric ovens. Multiple experiments were performed as part of the study. The results for the first experiment in the study confirmed that VR can be used as a valid alternative for product interface usability evaluation. The second experiment focused on evaluating the efficacy of the proposed methodology and tools and the results demonstrated that users are able to evaluate the usability of the product through virtual prototypes and are also able to analyze problems. The third experiment confirms the possibility of involving end-users during the design process and producing an improvement in the usability of the product's interface.

A VR-based tool for the participatory design of the workplace has been discussed in [55]. The resulting VR tool helped in addressing issues such as interface design and cognition during the design of workspaces.

A study has been presented involving civic participation in the design of a public park using VR in [56]. The results of the study indicate that 3D visualization helped both designers and untrained citizens to be more creative. The results also indicate that the participants using immersive VR headsets experienced a higher level of engagement during the design process compared to participants using non-immersive VR systems.

A study was conducted in [57] involving a group of older adults in which they engaged in creating VR-based ATM training simulation by using a participatory design approach. The results from the study demonstrate that VR is an effective way to directly gain valuable insights related to the design from the participants.

In [156], the authors have presented a unique participatory design approach in which surgeon-educators can include safety rules in the VR based laparoscopy simulator which can be automatically monitored. The proposed approach would provide immediate feedback to the users through visual feedback followed by a summary of snapshot messages to the instructor.

In [158], an environment and workflow were presented that let surgeon-educators create VR-based teaching modules. The focus was to make the VR-based modules accessible, modifiable, and sharable by the surgeon-educators. An open-source framework was developed in which surgeons fill a web-based form in which the surgical task was divided into main steps and tests were decided. Further, the surgeons could upload instructional multimedia illustrations for each step. Subsequently, they could upload or create virtual scenarios and customize them by changing elasticity, enabling feedback, among others. The authors' current focus is not the measurement of the final impact of the teaching module but how well their approach support surgeons in the creation of teaching modules.

In [159], the authors propose an approach to enable surgeon-educators to create VR-based environments. The objective is to create a bridging software that semi-automates the scene generation cycle in which the database of mechanical, collision and visual models are converted into working simulation through the utilization of blender and SOFA framework. Such an approach enables single-click testing of the physical behaviors of the anatomical scene.

2.6 INFORMATION MODELING

Information modeling supports the interdisciplinary approach in which experts from respective fields come together for the design of complex systems such as XR-based simulators [61]. In the information modeling approach, the emphasis is on the data/information exchanges that occur between the interdisciplinary team members along with the availability of tools and resources as well as information inputs and constraints which influence the design and development of a target system [62]. Information modeling has been used in the design and development of complex systems in domains such as manufacturing [58-61], surgery training [62-64].

Model-Based Systems Engineering (MBSE) approaches utilize such models to help define, design, and document a system which is under development. These models play an important role in providing an efficient way to explore and communicate the system aspects to the customers and stakeholders [65]. While some researchers have investigated MBSE approaches for domains such as naval ship design [66] and complex aerospace systems [67], there has been no reported adoption of advanced model-based approaches for medical simulator design and development activities. There has been a lesser emphasis in reported literature on research relating to the adoption of information models and work flow based techniques in the design and development of surgical simulators. One such approach [68], involves the use of a Workflow Integration Matrix (WIM) in the design of surgical information systems.

In [68], Jalote-Parmer proposed a framework called Workflow Integration Matrix (WIM) in the design of surgical information systems. WIM allows the decomposition of tasks into three surgical phases. The first phase was ‘Before Surgery’, the second was ‘During Surgery’ and the third was ‘After Surgery’. For each of the phases, the target state, surgical equipment, communication, patient state, and surprise state were noted. The WIM was developed in two steps. The first step involved the identification of task boundaries of the surgical workspace. The task boundaries laid the conditions for the completion of the task in terms of both possibilities and limitations. The second step involved the creation of a surgical problem-solving model which shows the interrelation of task boundaries. This helped in understanding the interconnection between various levels of the surgical process. The authors state that the proposed framework would provide the means for a better understanding of the surgical problem-solving process in the surgical workspace.

A Hierarchical Task Analysis (HTA) based approach has been proposed in [69] to analyze an endoscopic surgical process called Hybrid Rigid Scope Natural Orifice Translumenal Endoscopic Surgery (NOTES). In HTA, the main task is divided into subtasks hierarchically based on the overall goal of the task. A view of HT-based task division is shown in Figure 2.1. As seen in the figure, endoscopy surgery is divided into phases, tasks and subtasks. However, the flowchart does not include information regarding the constraints, the agents performing the tasks and the outcomes of the tasks.

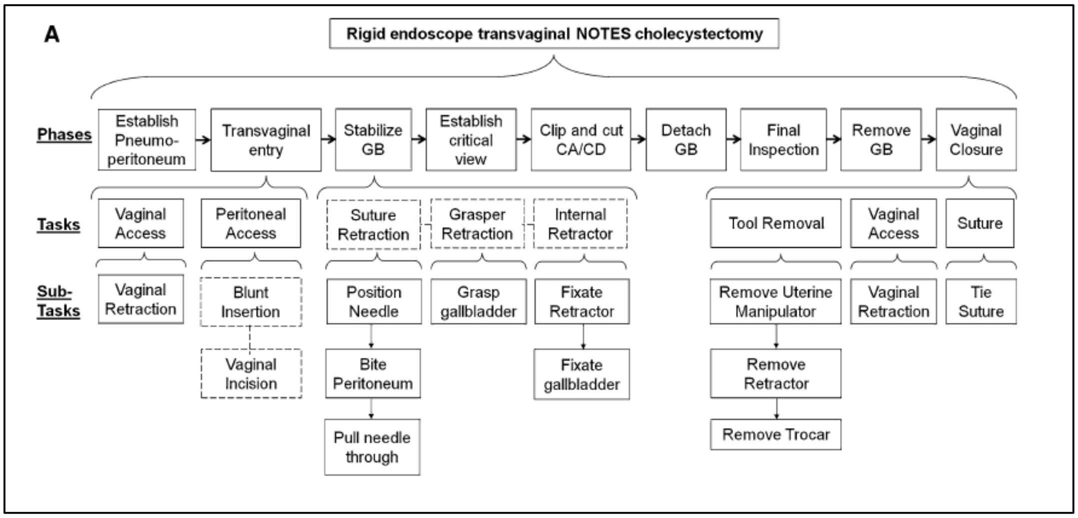


Figure 2.1. A view of the HTA flowchart for endoscopy surgery [69]

In [70], Jannin highlighted the need for process models in computer-assisted surgery; a global methodology was presented (in the context of neurosurgery processes) which included the definition of a surgical ontology, the software developed based on this ontology as well as the development of methods for automatic recognition of a surgeon's activities.

In [156], the authors have presented a unique participatory design approach in which surgeon-educators can include safety rules in the VR-based laparoscopy simulator which can be automatically monitored. The proposed approach would provide immediate feedback to the users through visual feedback followed by a summary of snapshot messages to the instructor.

The information models designed by other researchers such as WIM, HTA, and other approaches [68-70] do not model or capture key attributes such as information or physical inputs, and constraints; modeling such attributes is necessary to obtain a better understanding of functional and process relationships which in turn enables a stronger foundation that is necessary to build a simulator-based training environment or system.

The participatory design approach developed by other researchers [156, 158, 159] focuses on enabling surgeon-educator for automatic monitoring of safety rules and automatic generation of VR scenes. However, the research lacks the involvement of experts in each step of the creation of the VR environment (from idea generation to assessment). Further, the current research does not seek the involvement of experts in the creation of information models for the understanding of complex surgical procedure. The creation of information models following the participatory design approach can help the project team understand the complexities of the surgical procedure and enable capturing and representation of functional activities at various levels of decomposition. Further, it also facilitates checks and verifications which are needed to be addressed in the simulation scenario to better represent the actual surgical procedure. It also serves as a useful communication vehicle in the interdisciplinary team involved in the creation of the surgical training environments.

2.7 HCI BASED DESIGN CRITERIA

2.7.1 COGNITIVE LOAD

Learning systems should be designed in a way that provides appropriate levels of cognitive load to their users. Cognitive load theory categorizes cognitive load into two broad types: intrinsic and extraneous load [16]. 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. There are different types of methods used to assess the cognitive load on a user during the interaction with a simulator. They are broadly divided into (1) Subjective and (2) Objective Assessments.

2.7.1.1 Subjective Assessment

Researchers have developed and utilized a number of subjective methods to measure cognitive load. Some of the methods are the NASA TLX test [71], Paas Scale [72], among others. The Paas Scale measures the mental load of a person during a task; it consists of a Likert chart ranging from 1 (very, very low mental effort) to 9 (very, very high mental effort). The NASA TLX test measures the mental, physical, temporal demand, effort, and frustration using a 21 point Likert scale.

2.7.1.2 Objective Assessment

The objective assessment of the cognitive load can be categorized into:

a) Task-based Assessment

The cognitive load can be measured objectively by using a test called Dual-Task Measures. In this test, it is assumed that when the learning task becomes overloading, the level of performance in the secondary task decreases. The secondary tasks can be tasks such as pressing a button when the user hears a buzzing sound, identifying letters which are displayed on the screen, among others.

In [73], the cognitive load study during traditional cadaveric dissection training and VR simulation training was conducted using secondary task analysis; reaction to a sound stimulus was chosen as the secondary task. The results indicate that VR training leads to a lower cognitive load compared to traditional dissection. Secondary task analysis has also been used to measure cognitive load during VR-based temporal bone surgery and mastoidectomy training [74-75].

b) Assessment using Physiological Indices

Cognitive State or mental state can be measured using different modalities such as external physiological indices (pupil dilation, eye movement, and gaze, facial expression, etc.), central physiological indices (related to the central nervous system such as brain activity), and peripheral physiological indices (related to the peripheral nervous system such as muscle activity, heart rate, among others).

In [76], facial electromyography (EMG) was used to measure facial expressiveness while viewing pictures with positive and negative stimuli in an immersive VR environment. EMG is used to measure muscle activity by detecting tiny electric impulses and then amplifying them. The results indicate that facial expressiveness was measured accurately despite the interference of the head-mounted display (HMD) using EMG. Electroencephalography (EEG) was also used to classify facial expressions accurately when wearing an HMD using a machine learning algorithm [77]. EEG is a method to record brain activity by placing electrodes along the scalp.

Some researchers have measured various eye-related data to recognize facial expressions, confusion, emotional arousal among others [78-82]. In [78], users wearing HMD were asked to pose with various facial expressions; the images of their eyes were photographed using the eye-tracking camera which was later used to classify facial expressions using a machine learning algorithm. Eye fixation data coupled with a random forest machine-learning algorithm was used to classify confusion in [79]. Prior research also suggests that fixation duration can be used to indicate confusion [80]. Pupil dilation was monitored to measure emotional arousal in [81]. The results show that dilation was larger when emotionally arousing pictures were shown to the users.

In [82], multimodal physiological indices along with performance data were used to measure cognitive load in individuals with Autism Spectrum Disorder (ASD) when interacting with a driving simulator. Physicological data included pupil dilation recorded using eye trackers, brain activity recorded using EEG, and other peripheral physiological data such as muscle activity using electromyography (EMG), heart rate using electrocardiography (ECG) were recorded. The performance was recorded in terms of driving behavior, use of brake, and accelerator during the interaction with the simulator. The authors applied five classification algorithms viz. SVM, KNN, decision tree, discriminant analysis, and ANN to classify the cognitive load from the data. The multimodal data were fused in different levels viz. feature level fusion, decision level fusion, and hybrid level fusion. In feature level fusion, the input is feature vector which is features from each of the multimodal data such as eye gaze, EEG, peripheral data, and performance. The feature vector was normalized into a level of 0 to 1 and a classifier converts the input into output which is the level of cognitive load. In the decision level fusion, the classifier takes in the decision vector as input and outputs a sub-decision. The final decision is based on the weighted average of the four sub-decisions. They also showed that the weighted average vector can be found from a small number of selected weight vectors. The hybrid level fusion is a combination of feature and decision level fusion. In hybrid fusion, the feature level fusion can take input from two or three multimodal features and convert it into output which will serve as sub-decision, and decision level fusion can be applied using the output from the remaining features. The results show that multimodal information can be used to measure cognitive load with increased accuracy.

Lai [136] provided a systematic approach to evaluate 3D travel techniques such as automated travel, joystick-based travel, walking in place and scaled walking in terms of effectiveness, usability, and the cognitive load imposed on the users. The author used dual-task methodology to assess the cognitive load where the users performed n-back test and travel tasks based on Fitt’s law. Further, the authors summarized the usefulness of each travel technique including the pros and cons. In terms of accuracy, no difference was observed in the travel techniques. For accuracy, walking in place technique had a significantly higher score compared to scaled walking and human joystick techniques. The total time taken during scaled walking was significantly less than other walking techinques. In the trail time measurement, scaled walking cost significantly less time. For ballistic time, human joystick required significantly more time. The participants spent less time for refinement in scaled walking. Further, the particpants could exit the way-point significantly faster with scaled walking. The subjective studies showed that there was no significant difference in the walking techniques. The scaled walking technique was significantly more realistic compared to others. For the simulator sickness score, the human joystick received significantly higher score. In terms of perceived usability, scaled walking was significantly better compared to other techniques. Lai has also provided some design guidelines based on results such as usage of time efficient travel technique to redure cognitive load, usage of automated travel if there is no need of user control, usage of scaled walking if travel distances are limited, avoidance of human joystick technique if simulator sickness is of concern, avoidance of torso-directed steering if steering metaphor travel technique is desired.

Martens et al. [161] studied the effect of stressors during the interactions with VR based environments showcasing an elevator. In the VR based environment, the users traveled up outside a tall building and were asked to step off the elevator platform. 28 participants interacted with the simulator with and without the stressor. The psychological and physiological stress indices such as skin conductance, blood pressure, salivary cortisol, and alpha-amylase were measured. The results from the study show that the participants interacting with the stressors had increased skin conductance, pulse, altered heart rate variability, and subjective stress and anxiety ratings.

Moorthy et al. [162] studied the impact of stress-inducing conditions on the performance of a laparoscopic task. In the study, the participants performed a laparoscopic transfer task under five conditions viz. verbal math tasks, background noise, performance as fast as possible, a combination of all three stressors, and no stressors. A total of 13 surgeons with varying levels of experience interacted with the simulator. The effect of the stressors was assessed by using a motion analysis system. The results of the study show that there was a significant increase in path length of the right hand under the stress of time and a significant increase in path length of the left hand under the stress of the mathematical task, time, and combined stress. The authors concluded that the stressors led to a decrease in dexterity and an increase in errors.

Peterson et al. [163] studied the effect of VR based high heights exposure on physiological stress. A total of 19 participants interacted with two VR based scenarios (beam walking at high height and low height). The results of the study show that the virtual high height condition caused increased heart rate variability and frequency compared to the low height condition. The results show that the participants interacting with the high height condition showed decreased dynamic balance performance and increased cognitive load compared to the participants interacting with the low height condition.

Previous work on cognitive load mostly focused on assessing the load on the users using various subjective and objective assessment techniques. Researchers have not focused on developing scenarios within the VR environments which would affect the load on the users. Few researchers have used dual-task measures depending on basic tasks such as buzzing sound, identifying letters, among others. However, such tasks are completely unrelated to the process being performed in the VR environment. In the proposed framework, the tasks related to the process (surgical training) being performed in the VR environment are being used to measure the cognitive load on the users.

2.7.2 AFFORDANCE

The word affordance was first coined in [83] 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 [17]. Gaver delineated affordances as the properties of the world which are defined with respect to how people interact with them. Gaver provided an analysis of the relationship between affordance and perceptual information about the information which led to four possible combinations viz. perceptible affordance, false affordance, hidden affordance, and correct rejection. In perceptible affordance, there is perceptual information available for affordance. In the case of false affordance, perceptual information is not available for affordance. When perceptual information is available but affordance is not, it is known as a hidden affordance. When both perceptual information and affordance in unavailable, it is called correct rejection [84].

During the design and development of XR-based applications, designers focus on spatial, manipulation, and feedback affordances [85]. Head-mounted XR-based displays provide natural movement of the head and body which enables users to sense the depth of images in an intuitive manner 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. Manipulation of virtual objects is a key activity a user performs in any XR-based environment. Manipulation affordance is the affordance offered by manipulating or interacting with the virtual object in an XR environment. Affordance can also be achieved by providing feedback to the user without any latency. The user should be able to see the result of the action (such as picking up an object) instantaneously on the XR display.

Schirm et al. [86] measured presence in a VR environment where the users had to locate 7 items in a VR environment. Two events were designed to measure the presence which was (i) the swing of a chandelier and (ii) a ghost appearing. Head movement distance was calculated when the chandelier swung and head movement speed was measured when the ghost appeared. Head movement speeds of a startle response produced the most distinct results in our study, especially in conjunction with bounding box dimensions of the head movement trajectory. Participants whose reaction was classified as strong had more experience (mainly with VR), felt more present, and were more impressed with their VR game.

Pointon et al. [87] developed a test for objective assessment of judgment and action-based measures to measure perceptual fidelity in AR using HoloLens. Observers were asked whether they pass through a holographic aperture presented at different widths and distances using virtual poles and then to judge the distance to the aperture. Distance between poles varied from 60 cm to 30 cm and changed every 7 seconds by 5 cm. A crossover point was set which was the largest aperture width at which participants stated they could no longer pass through for at least two consecutive trials. The ratio between the crossover point and the participant's shoulder width was noted. If ratio >1, participants overestimated the size of the aperture needed to pass through, and if ratio <1, participants estimated that they could pass through an aperture that was smaller than their ability. Passing through estimates were relatively accurate, but somewhat larger than actual shoulder width (Mean ratio = 1.18). This is consistent with classic findings in the real world on affordances for passing through.

Wu et al. [88] conducted a similar study in which gaps of varying widths and depths were placed in AR using HoloLens and users were asked if they will be able to step across the gaps. As predicted, the results revealed a significant effect of pit depth on users' judgment. Planned contrasts with the deep pit as the reference showed that participants underestimated their capability to step over the gap when presented with the deep pit relative to the shallow pit. There was no difference between judgments for the medium and the deep pits.

Regia-Corte et al. [89] studied the Influence of person and environmental properties in the perception of standing on virtual grounds. Three studies were conducted which were

- Study 1: Determine whether a wooden surface with a given inclination support the upright posture

The results from the first study concluded that participants made a distinction between those inclines that appeared to support upright stance and those that did not. Participants took longer to explore surfaces close to the transition point between supporting and not supporting upright posture and participants were less confident of their responses close to the transition point.

- Study 2: Perception of standing on a slanted surface by considering VE properties

The results revealed a significant effect of texture in the perception. The users felt that it was no longer possible to stand on ice texture at 22.13 degrees and wood texture at 27.60 degrees. This suggests the virtual information was detected.

- Study 3: Considering user's position on the slanted surface

The results indicated that a person's position on the slanted surface was involved in the perception of affordances for standing on this surface in VR.

Van Vugt et al. [90] tested the effect of aesthetics (beautiful versus ugly) on the affordance of the interface. The authors tested the effects on users' intentions, engagement, and satisfaction. Sim2 game was used to test the effects and the results show that people tended to use helpful characters more than obstructing characters and user engagement was enhanced by the beauty and perceived affordance of the character. However, the intentions to use the character were not affected by good looks.

Gagnon et al. [91] conducted an experiment to test the egocentric distance perception in AR. Two real-world settings; a large open room and hallway was used for this experiment. A 1.8 m AR avatar was placed at 10, 15, 20, 25, 30, and 35 m and the users were asked to estimate the distance of the avatar. The results of the experiment showcase that the participants underestimate the distance to AR avatars.

Ke et al. [92] investigated the affordances and constraints of a VR-based learning environment for the teaching training targeted towards graduate teaching assistants in relation to task, goal-based scenarios, learning support design. A total of seventeen participants interacted with OpenSimulator supported teaching program. The results of the study show that VR-based learning environment fostered participants' performance. VR-based environment helped them notice and attend to students' actions and reactions.

Li et al. [93] conducted an experiment to understand the difference between people's cognition of operation and the form of product presentation. They explored the gender-based visual perception for the interface design of smart washing machines. The results demonstrated that gender differences significantly affect the sensitivity of perceiving smart technology products.

Koutromanos et al. [94] examined the potential educational affordances of Augmented Reality (AR) for pupils with Moderate Learning Difficulties (MLD). Three open questions were asked to 25 teachers who specialized in AR. The responses revealed 10 affordances viz. in situ contextual information, individualized guidance, feedback, gamified experiences, learning object visualization, interaction reinforcement, ability to obtain first-person view including three new affordances viz. attention capturing, skill development efficiency, and repeatability.

Thompson et al. (21) explored the affordances in computer-based assessment through the development of 3D science learning. Task-based interviews were performed to compare the 3D environment to multiple-choice questions. The results show that the 3D items are more or equally effective to MCQs.

Matuk [95] focused on understanding the learning affordances of AR for museums. The authors revealed four major affordances for AR which were Spatial and Temporal Representation, Narrative and Interactive, Real-time, Personalized Scaffolds, Collaboration. They also suggested few issues such as gimmickry and privacy concerns for the user of AR in museums.

Bower et al. [96] illustrated various educational affordances of wearable technologies. 66 educators were provided a survey regarding the affordances of wearable technologies. A framework which included 14 affordances and 13 issues was created from the responses which were categorized into three themes; pedagogical usage, educational quality, and logistic.

Ricca et al. [97] compared touch-based and head-tracking navigation technologies for aVR-based biopsy simulator. The study compared two viewpoint-changing techniques with two levels of interaction fidelity in which 21 novice users participated. Objective test (time, precision, and error) and subjective survey (5-point Likert scale) was conducted and the results show that touch-based viewpoint movement improved the task completion performance.

Macchini et al. [98] compared different viewpoints and users of VR on the operation of a fixed-wing drone. 30 volunteers participated in the study in which the body motion analysis was performed and a presence questionnaire was provided. The results showed that VR correlates with a higher sense of spatial presence and spontaneous body motion patterns were affected by VR.

Gagnon et al. [99] studied the effect of feedback on action capabilities for two reaching behaviors (reaching out and reaching up). The results show that reach was initially overestimated. However, the estimations became more accurate over the feedback blocks.

Readman et al. [100] investigated the influence of perceptual-motor variability on perceived grasp ability in Virtual Reality. Participants estimated grasp ability after an experience with four types of grasps; constricted, normal, extended, and variable. Two experiments were conducted; in the first experiment, the participants experienced all three grasps 33% of the time and in the second experiment, they experienced constricted and normal grasps 25% of the time and extended grasp 50% of the time. The results show that if the feedback is inconsistent, the perceptual system disregards the experience with different action capabilities.

Keshavarzi et al. [101] explored non-verbal communication features for VR and AR-mediated communication settings. Four interaction methods were chosen for the study; face to face interview, zoom call, Virtual reality-based Avatars, and AR-based Holograms. The results showed that over 75% of participants ranked 2D video as their first choice. Participants narrowly preferred holograms over VR. The acceptance rate of hologram and VR increased in less emotionally engaged conversation tasks.

Gordon et al. [102] three experiments to understand the learning affordances for word learning in VR. The results of the first experiment showed that direct manipulation induces affordances for word learning. The results of the second experiment underscored that virtual hands interacting with the objects affect affordances. The results of the third experiment showcased that affordance was affected mostly by the compatible hand and not by the spatial location.

Dobriki et al. [103] conducted a study to study the utility of VR for teachers in which 10 horticulture teachers interacted with VR environments to study the planning of the garden. The results of the study showed that the VR was rated higher in educational usefulness and the teachers felt more present in VR.

Bhargava et al. [104] compared passability judgments in the virtual environment and real world. Participants were asked to judge if they could pass through a sliding doorway which was adjustable wearing an HTC Vive headset. They were also allowed to walk if they were not sure of their judgments. The results show that participants can judge possibility effectively both in VR and real-world. However, the participants made more movements in VR to acquire the passability information.

Nolen et al. [105] compared students’ engagement and interest in engineering between virtual and physical laboratory projects, designed to be realistic and replicate engineering practice. 118 students' interest and engagement in two physical laboratory projects and one of two virtual laboratory projects in a senior-year capstone course were investigated. Students reported greater engagement, perceptions of contribution to their group's learning, opportunities to transfer prior learning from coursework, and end-of-course interest in engineering problem-solving in the virtual laboratory project rather than the physical laboratory projects.

2.7.3 DISTRACTIONS

Li et al. [106] studied the level of presence in a VR-based operating room developed for laparoscopy training. Thirty-seven surgeons and surgical trainees interacted with the simulator and were asked to complete the survey based on the Presence questionnaire. The results indicated that participants, especially the young trainees were excited to interact with the simulator. 25 out of the 37 participants indicated that the talk and the sounds in the environments enhanced the presence.

Graafland et al. [107] studied the situation awareness of participants during surgical training in a smartphone-based minimally invasive surgery serious game in which a problem scenario was introduced and users had to solve it using correct actions. 45 surgeons, medical students, and residents who interacted with the serious game were surveyed and the results show that the majority of participants had a positive attitude towards the game and the situational awareness scenario presented in the game.

Gardner et al. [108] studied the feasibility of the Situation Awareness Global Assessment Technique (SAGAT) tool to assess situational awareness in the surgical trainee. 43 third-year medical students interacted with two scenarios developed for advanced cardiac life support as part of ten-team training sessions. SAGAT method involves freezing the simulation and probing the trainees with questions. The results show that it is feasible to measure situational awareness using the SAGAT tool in a simulated team setting.

2.7.4 VISUAL DENSITY

Few researchers have focused on understanding the impact of visual density and information density during the interaction with VR and AR environments [109, 110]. In this research, a study is proposed to understand the effect of varying visual density on the affordance of an AR environment. The varying density is based on a varying number of surgical equipment and instruments, avatars, and other objects of interest in the AR/VR environments.

Current research on visual density focus on information density (number of dots in an environment, locating a letter in a visual dense scene) without taking into account the varying density is based on a varying number of surgical equipment and instruments, avatars and other objects of interests in the AR/VR environments.

2.7.5 REPETITION EFFECT

Brunner et al. [111] studied the effects of repetition on a VR-based laparoscopy simulator. 12 second-year medical students participated in the VR-based training. The participants performed 30 repetitions of 12 different tasks in the VR-based simulator. For each task, two to seven plateaus were identified. Initial plateaus were identified by the eighth repetition for all the tasks. The final plateaus were not reached until 21 to 29 repetitions.

Kang et al. [112] studied the impact of repetition on the Vesicourethral anastomosis simulator. The participants were divided into three groups. The first group interacted with the simulator for 1 hour for 4 consecutive days. The second group interacted for 1 hour weekly for 4 days and the third group interacted with the simulator for 4 hours in just one day. The users who interacted with the simulator for 1 hour for 4 consecutive days performed the best among the three groups.

Current work on affordance mainly focused on spatial affordance. The researchers focused on how basic tasks such as passing through a door, an aperture, observing gaps are afforded in virtual and augmented reality. There hasn't been any research focusing on spatial affordance during complex tasks. As most of the VR 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 a VR environment using various subjective and objective questionnaires. 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 VR environment.

2.8 ASSESSMENT METHODS

2.8.1 KNOWLEDGE ASSESSMENT

Few researchers have studied the impact of using XR simulators for medical training by conducting pre and post-tests with participants [113-115]. A pre and post-test based method was utilized to measure the subjective experiences of the trainees for VR-based endoscopy surgical training in [114]. A low-cost VR simulator to train residents increasing surgical oncology capacity and capability was discussed in [115].

2.8.2 SKILLS ASSESSMENT

Researchers have also adopted skills-based assessments to better understand the impact of using VR-based training simulators. They have focused on conducting assessments within the simulator to assess the skills of the users [116, 117]. An in-simulator assessment environment to test the decision-making skills pertaining to blunt thoracic trauma was proposed in [117]. A VR-based simulator for skills assessment of catheter/guidewire manipulation for cardiovascular interventions was elaborated in [116]. In [118, 119], skills-based assessment was performed for shoulder arthroscopy surgery in which the users had to locate and probe a simulated target within the shoulder joint using a simulated arthroscope.

Ausburn et al. [135] compared the effectiveness of VR with traditional still color images presenting an operation theatre in terms of six aspects viz. (a) accuracy, (b) recall, (c) perceived confidence, (d) perceived difficulty, (e) time on learning, and (f) time of scene orientation. 31 surgical technology students with high (HV) and low levels (LV) of perception skills participated. The results demonstrated that HVs were more confident with VR and LVs were more confident with still images. HVs found tasks easier in VR whereas LVs found it more difficult. LVs performed better in one complex task with still images and HVs performed better in VR.

Knowledge assessment does not assess the skill level of the users and skills-based assessments do not evaluate the knowledge gained by the users after learning interactions with a simulator. There is a lack of an integrated assessment approach involving assessment of comprehension, skills, and knowledge as well as the cognitive load imposed on the users.

2.9 NETWORKING

Collaborative virtual environments enable distributed users to interact with each other [120-123]; it enables surgeons and residents to perform training activities in a collaborative manner from remote locations. Morris et al. [120] described a collaborative virtual environment for temporal bone surgery which used a private gigabit ethernet intranet. By the use of intranet, the voxel-based bone model was used for training interactions from both locations.

A Collaborative surgical system with a haptic interface is discussed in [121] which implemented a haptic-based system in which the users could simulate surgical processes using virtual tools independently in two different locations. Paiva et al. [122] described SimCEC which is a cloud-based collaborative virtual environment for surgical education.

A middleware platform was discussed in [123] for efficient collaboration using series of network management approaches such as service management, collaboration mechanisms, various deformation models among others. A review of networking approaches in distributed surgical simulation indicates that while some approaches support distributed collaboration and remote access, they have not explored the adoption of Next Generation Internet technologies such as cloud computing and Software-Defined Networking (SDN). SDN and cloud computing have been adopted in the network-based approach presented in this paper. SDN not only reduces the complexity seen in today's networks but also helps Cloud service providers host millions of virtual networks without the need for common separation isolation methods [124].

A review of networking approaches in distributed surgical simulation indicates that while some approaches support distributed collaboration and remote access, they have not explored the adoption of Next Generation Internet technologies such as cloud computing and Software-Defined Networking (SDN).

2.10 VOIDS

In table 2.1, the current research being performed in the domain of XR-based training environments has been summarized. As summarized in the table, the past research has only focused on certain aspects essential to design XR-based traiing environments but not on creating a comprehensive framework. Further, the past researchers have only focused on the participatory design approach and there is a lack of proper utilization of the participatory design approach during the creation of information models. Moreover, the past researchers have not utilized a systematic process in the understanding and identification of HCI-based criteria for the creation of simulation-based training environments. There is also a lack of an integrated assessment approach involving assessment of comprehension, skills, and knowledge as well as the cognitive load imposed on the users. Table 2.1. also shows the various aspects of the XR-based framework which are part of the current research presented in this dissertation.

	Aspects of the XR Framework									
	HCI Criteria			Information Centric Approaches		Computational Approaches	Networking Approaches	Assessment Techniques		
Paper	Affordance	Cognitive Load	Visual Density	Participa-tory Design	Information Modeling	Use of Algorithms	Collaborative training environments	Skills Assessment	Knowledge Assessment	Subjective Surveys
Bhargava	✓									
Regia-Corte	✓									
Karanam	✓									
Anderson		✓								
Britt		✓								
Miscovic		✓								
Jain				✓				✓		
Lovquist				✓				✓		✓
Trepkowski			✓							
Berton			✓							
Fang									✓	✓
Gonzalez								✓		✓
Shao									✓	✓
El Hariri						✓		✓		
Vankipuram						✓		✓		
Choi						✓		✓		
Westwood								✓		✓
Nemani					✓					
Janin					✓					
Parmer					✓					
Paiva							✓			
Morris							✓			
Chebbi							✓			
Required for Holistic Framework	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓

Table 1.1. Current Research in development of XR based training environments

2.11 CONCLUSION

In this chapter, relevant literature related to the HCI based framework and the components associated with the framework was presented. Related work in domains such as XR based surgical simulators, HCI, participatory design approaches, information modeling, assessment approaches and networking has been discussed. Finally, a table showcasing the current research in the design and development of XR training environments was presented.

In the next chapter (Chapter 3), the design of the XR based environments based on information modeling is discussed. The creation of XR based training environments, challenge scenarios and integrated assessment scenarios are elaborated in Chapter 4. In chapter 5, the overview of the assessment activities is presented. In chapter 6, 7, and 8, the results from the assessment activities are showcased. The conclusion is discussed in chapter 9.

CHAPTER III

DESIGN OF HCI BASED FRAMEWORK FOR CREATION OF XR BASED TRAINING ENVIRONMENTS

3.1 INTRODUCTION

In this chapter, the design of the HCI-based framework based on participatory design and information modeling approaches is presented. Before the discussion of such approaches, an overview of the various components of the HCI-based framework is presented in section 3.2. The discussion of the modeling foundation for the participatory design approach is provided in section 3.3. In section 3.3.1, the participatory design approach is discussed followed by the discussion of the information modeling approach in section 3.3.2. The information models created to understand the complex surgical procedure are also showcased in section 3.3.2. The process models developed to understand the process of creation of the XR-based framework are discussed in section 3.3.3.

3.2 OVERVIEW OF THE HCI BASED FRAMEWORK

This research proposes a holistic framework for XR-based training environments comprising of participatory design, creation of information-centric models, HCI design and assessment, computational approaches, next generation networking, and integrated assessment approaches. Figure 3.1 shows the components of the framework and how the components are interconnected in order to form the holistic and integrated framework. As seen in Figure 3.1, the information modeling approach serves as a foundation for the creation of the XR environments and also helps in the selection of HCI criteria. The HCI criteria are utilized during the design of the XR environments and also during the assessment approach in which the focus is to understand the impact of such criteria on the skills and knowledge acquisition of the users. Novel computational approaches such as penalty-based A-star and genetic algorithms have been utilized for the creation of the XR-based environments. Further, next generation networking is utilized to support collaborative training using the XR-based environments from remote locations.

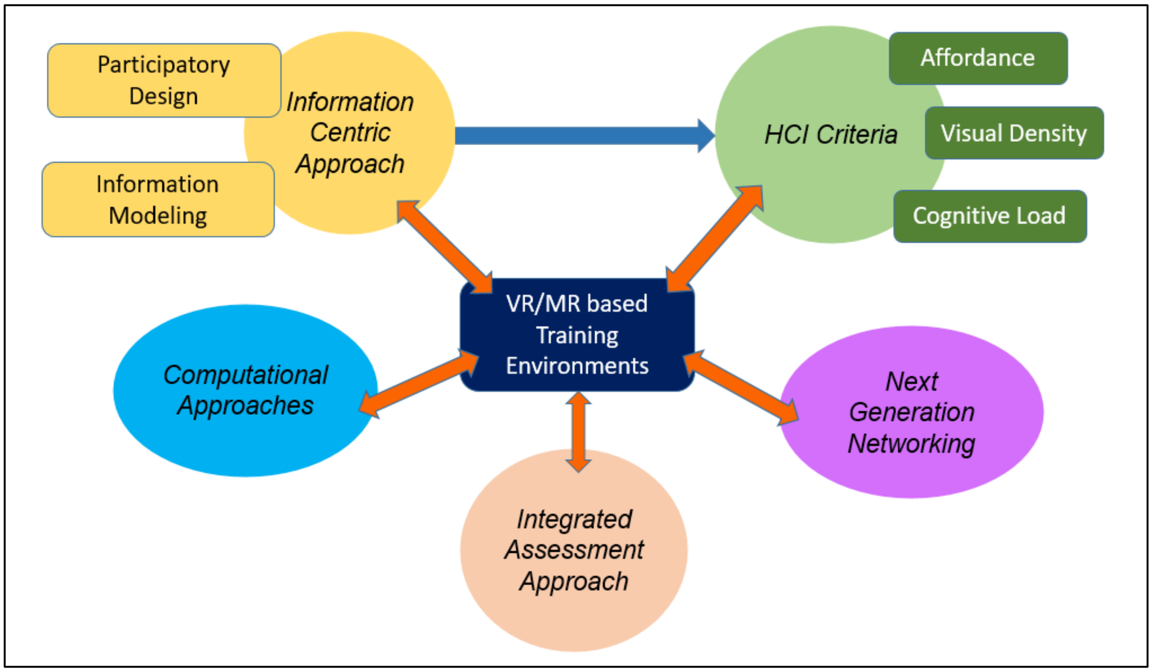


Figure 3.1 Components of the HCI based Framework

3.3 MODELING FOUNDATION FOR PARTICIPATORY DESIGN

The past researchers have only focused on the participatory design approach [51-57], 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. An elaboration of the participatory design approach and information modeling is presented in the following section.

3.3.1 PARTICIPATORY DESIGN APPROACH

The participatory design approach is a democratic design process for the design of social and technological systems based on the argument that users should be involved in the design and all stakeholders should have input during the design process [19]. In the participatory design approach for the Cyber-Human framework for orthopedic surgical training, three expert surgeons provided input on several design aspects of the VR-based environments for condylar plating surgical procedure under the coordination of the lead expert surgeon. Detailed knowledge and understanding of the condylar plating surgical process were required before creating the VR framework. The participatory design approach involved first understanding the condylar plating surgical procedure through interactions with expert surgeons. The expert surgeons helped in dividing the entire process of condylar plating into five phases.

3.3.2 INFORMATION MODELING

Based on the understanding of the surgical procedure provided by the expert surgeons, information models were created. However, information models designed by other researchers such as WIM, HTA, and other approaches [68-70] do not model or capture key attributes such as information or physical inputs, and constraints; modeling such attributes is necessary to obtain a better understanding of functional and process relationships which in turn enables a stronger foundation that is necessary to build a simulator-based training environment or system.

The information models presented in this research consist of functional entities and associated attributes relevant to identified steps. The information modeling approach presented in this research has been used previously in the design and development of complex systems in domains such as manufacturing [58-61, 137-141], surgery training [165-170], space systems [144-146] and education [148-155]. This modeling approach was first used to develop an information model of fixture design activities and subsequently used as a basis to design and build an automated fixture design system [61, 164]. Further, this modeling approach is used for the modeling of the virtual prototype for microdevices assembly [62-64]. In this modeling approach, Cecil described three categories of information attributes for each entity: the Influencing Criteria (IC), the Performing Agents (PA), and the Decision Outcomes (DO). Using these attributes, a target set of phases can be modeled, studied, and analyzed at various levels of abstraction along with key relationships among these phases. Influencing Criteria can be information inputs and constraints that directly impact the accomplishment of the target phase. Constraints can be viewed as controlling factors influencing the phase being modeled. The information inputs are the information attributes that are required (and can be viewed as process drivers) to accomplish the target phase. The Performing Agents (PAs) refer to the software, personnel, and/or machines/tools agents that perform the identified phases. Decision Outcomes (DO) can be grouped under information and physical objects and encompass the information or physical outcomes (respectively) of phases performed.There is an intermediate tracking of the surgical outcome in order to ensure the satisfactory progress of the surgery; feedback arrows are used to ensure that relevant follow-up is completed before the next step is initiated. The top-level waterfall process model depicting the condylar plating surgical procedure developed through the participatory design approach is shown in Figure 3.2. The decomposition models for the top-level model are shown in the appendix. The decomposition models illustrate the ICs, PAs, and DOs for each of the entities described in the top-level model (Figure 3.2) in a detailed manner.

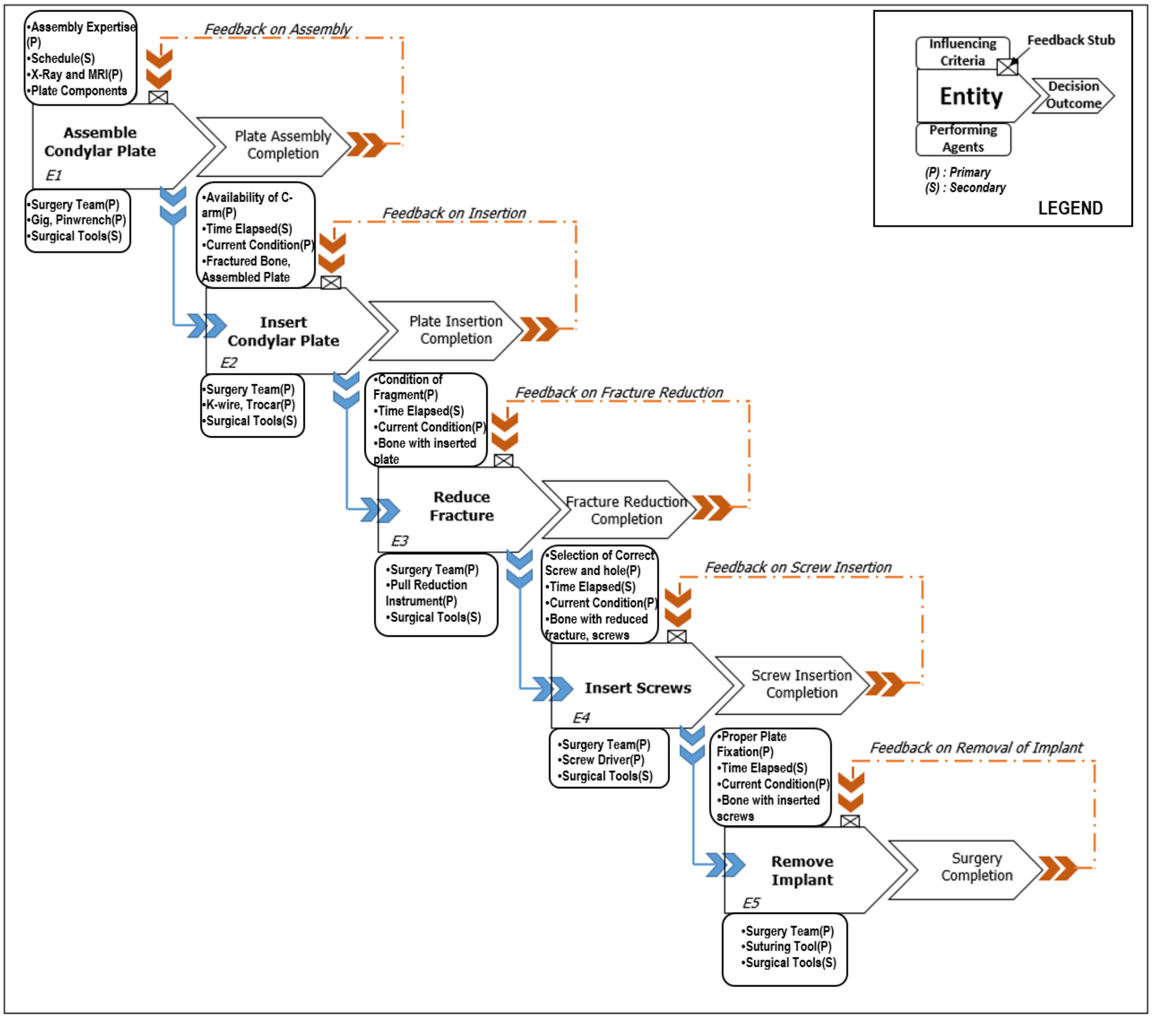


Figure 3.2.: Top-level Waterfall eEML model depicting the Condylar Plating Surgical Procedure

Benefits of building this information model using the participatory design approach:

a. Provided an effective and detailed basis for the project team to understand the complexities of the activities and the inter-relationships between them; this, in turn, provided a structured foundation for the creation of detailed simulation training scenarios which reflected the complexities of the surgical process sequence

b. Enabled capturing and representing the functional activities at various levels of abstraction (or decomposition)

c. It also facilitated ‘checks’ and ‘verifications’ which needed to be addressed in simulation scenarios within each step in a sequence of surgical tasks that reflected the physical surgical process

d. Served as a useful communication vehicle between the expert surgical team and the various members of the IT/engineering team involved

3.3.3 PROCESS OF DESIGNING THE XR BASED ENVIRONMENTS

Detailed knowledge and understanding of the condylar plating surgical procedure were required before building XR-based training environments. The information model depicted in Figure 3.2 served as a use case for the creation of the information model showcasing various entities and attributes involved in the design and development of the XR-based training environments. The information model showing the six phases of the design and development process is shown in Figure 3.8. A brief discussion of the six phases follows.

Phase 1: Understand and identify simulator requirements (E1)

When developing any software system (the XR training environments, in our case), it is important to understand the expectations of the customers (which in our case included surgeons and residents) and their objectives in creating the target system.

In this phase, the focus was on understanding and identifying the simulation system and surgical training requirements. Three expert surgeons served as knowledge sources for this project. Discussions and interactions with the expert surgeons lead to gaining a better understanding of the overall simulator requirements including platforms desired, user interface preferences, and specifications. The eEML model reflects the main attributes of these activities; the information inputs include the surgical training objectives. The main output (or decision outcome) of this activity was the identification of the software system and surgical training requirements which need to be addressed when building the simulator.

To support this activity, several meetings and discussions were conducted with the expert surgeons; additional skype based meetings, as well as a review of videos of physical surgical procedures, were also conducted to gain a better grasp of the surgical contexts involved. This set of functional requirements and training requirements provided the basis for the design and development of the simulator.

Phase 2: Understand the surgery (process) domain (E2):

The output of Phase 1 was surgical training requirements which included identifying the type of surgical procedures (which were the focus of the training activities), the computing platform and software to be used as well as the skills to be acquired as outcomes of this training procedure, among others. Based on these requirements, it was important for the design team to understand the intricacies of the various tasks within the steps of the surgical procedures (condylar plating surgery). This was addressed by reading books, reports, and papers, studying videos of condylar plating surgery as well as interviewing and conducting discussions with expert surgeons, among others. The primary outcome of this important phase is the understanding obtained of the condylar plating surgery, which provided a strong foundation for the remaining phases in this overall process.

Phase 3: Design the XR based training environments (E3):

After the development of the eEML models, the next phase was to create software design models based on the eEML process or information models. These software design models were created to serve as a basis for the development of the simulator. The emphasis in this phase was on designing the simulator including developing the modular architecture, identifying the various functional modules (including the training modules and their scope, the user interface modules, etc.), and studying and analyzing various HCI-based aspects. The main outcomes of this phase are software design models reflecting the overall design of the; these include diagrams such as sequence, communication, and class diagrams based on the UML. These software design diagrams were used as the basis for the next activity (involved building the training environments).

Phase 4: Build the XR based training environments (E4)

These phases involved building the training environments using various software tools and XR equipment. Adopting the information models enabled identification of the tools to be used in building this environment including the Unity 3D engine (which was used for the main simulation environment building activity), Blender, and Solidworks (which is a CAD modeling tool used to create the various 3D models for the various simulation scenes). The primary outcome (DO) after completion of this phase is the completed simulator-based training environments.

Phase 5: Perform learning interactions (E5):

It was important to verify the correctness of the training environments before it could be used as a training tool. The role of the expert surgeons and the medical residents along with the overall process steps was identified early in the design process. In general, the expert surgeons first interacted with the various modules of the training environments to ensure their correctness, scope of training, and level of detail. As the training environments development progressed, timely feedback was provided by expert surgeons to make changes to the training environments' contents to ensure correctness as well as initiate modifications to add or reduce detail or incorporate specific training nuances to various surgical training tasks; these were then implemented in the simulator; subsequently, assessment of learning using these simulators was performed involving medical residents and students.

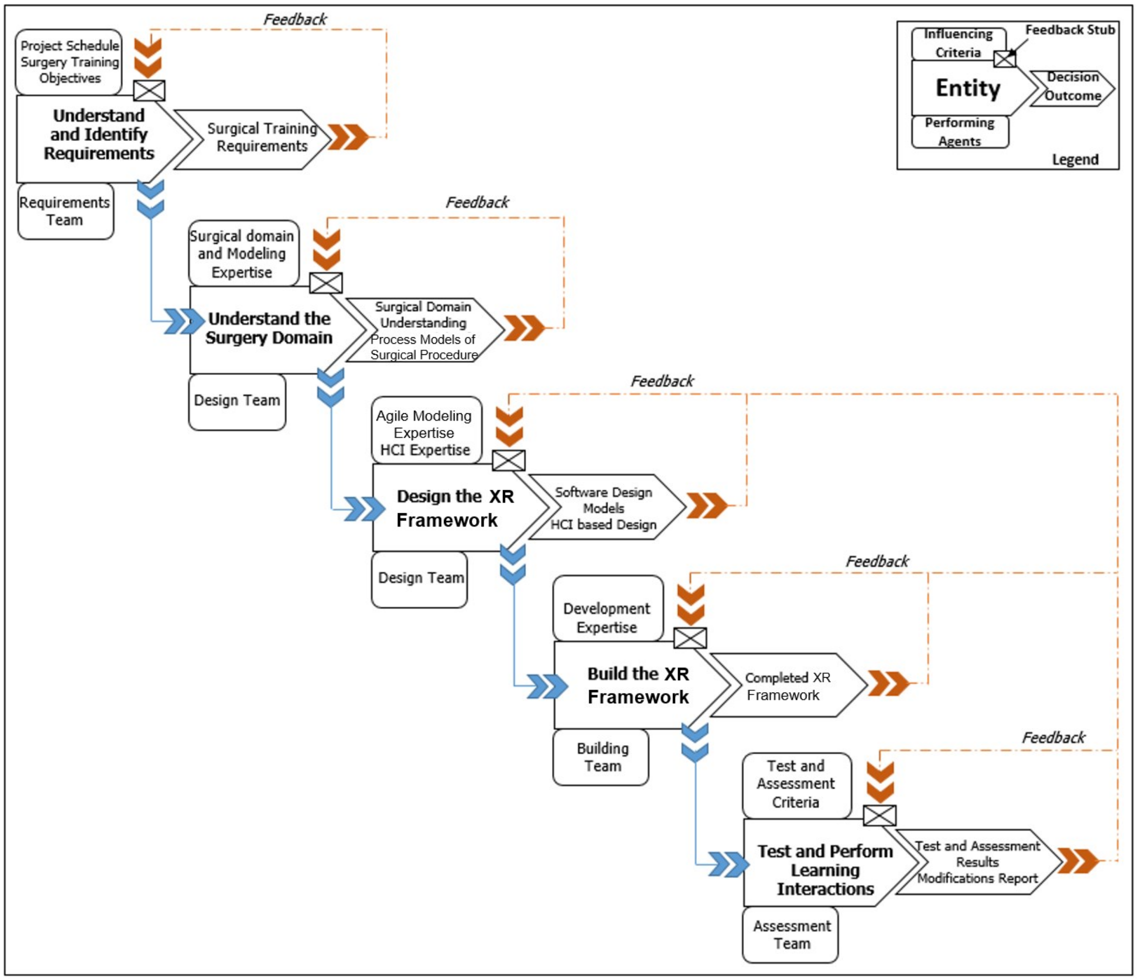


Figure 3.3. Elided eEML model depicting the process of designing and developing the XR based training environments

3.3.4 FEEDBACK FROM EXPERT SURGEONS

Apart from the creation of the information models, the expert surgeons also provided feedback during the design and development of the XR-based training environments. Before the assessment activities, expert surgeons reviewed the training environments. The suggestions and feedback from the expert surgeons were incorporated to develop the modified training environments. A few of the suggestions from the expert suggestions follow. The expert surgeons suggested a red light/green light-based training approach for the plate insertion and position which went through many iterations. They also suggested creating a training environment to reduce non-essential hand movements. Some of the expert surgeons were not satisfied with the operation room setup. They suggested including more equipment, machines, tools, cabinets, among others so that the room looks more realistic. In order to increase the realism, they also suggested using sounds and noises in a typical operating room and increasing the number of avatars which would serve as nurses, surgery assistants, anesthesiologists, etc. Other suggestions included repositioning the text cues to face the users, positioning the users such that the hand model picking up the tool and equipment do not block the line of sight of the users.

3.4 CONCLUSION

In this chapter, the design of the HCI-based framework based on the participatory design approach and information modeling approach was presented. Information models created using the eEML modeling language to understand the complex surgical procedures were also presented. Further, the information models created to understand the process of creation of the framework were also discussed in this chapter. Finally, a section focusing on the feedback and suggestions provided by the expert surgeons for modification and improvement of the XR based training environments was also included in this chapter.

CHAPTER IV

DEVELOPMENT OF HCI BASED FRAMEWORK FOR CREATION OF XR BASED TRAINING ENVIRONMENTS

4.1 INTRODUCTION

In this chapter, a detailed discussion of the HCI-based framework developed for the creation of XR-based surgical training environments will be presented. Further, an elaboration of the components of the framework such as HCI-based design criteria, XR-based training environments, integrated assessment approach, and next generation networking will be presented. Finally, the design of experiment tables for the experiments showcased in the upcoming chapters will also be discussed.

4.2 XR BASED TRAINING ENVIRONMENTS

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. A view of the condylar plating surgical procedure is shown in Figure 4.1. In the early part of the research, immersive and haptic based Less Invasive Stabilization System (LISS) plating VR based training environments were developed [166-169]. LISS plating is also performed to treat the fractures of the femur bone. The LISS plating simulator served as a foundation for the development of more complex XR based training environments for the condylar plating surgical procedure [170-174]. The VR-based environments were developed for Vive Pro immersive platform and the MR-based environments were developed for the HoloLens 2 platform. The XR 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. The views of the LISS plating training environments are shown in Figure 4.2. The views of the XR based condylar plating training environments and the users interacting with environments are shown in Figure 4.3 respectively.

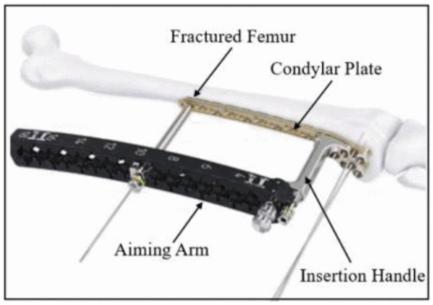
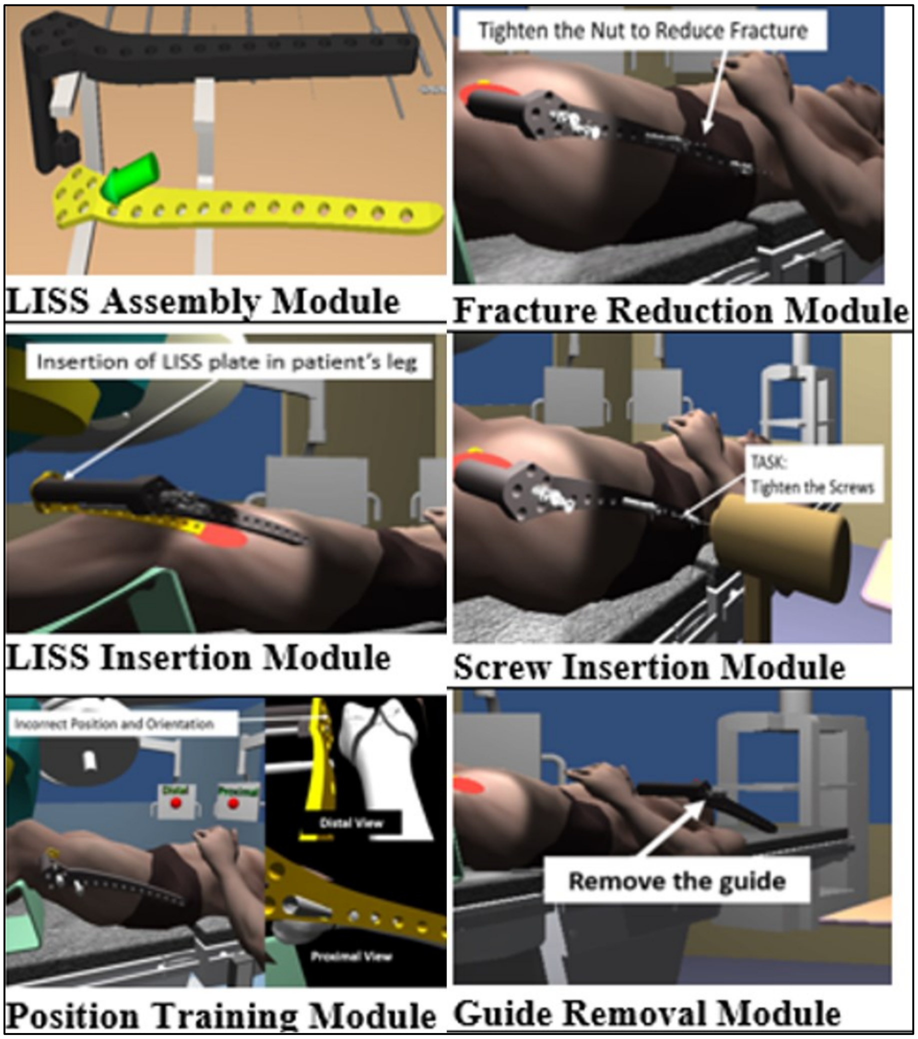


Figure 4.1. A view of the condylar plating surgical procedure

A total of four training environments were developed for the training. Two out of the four training environments were developed for both VR and MR-based training and two training environments were developed only for the VR-based training. Table 4.1 shows the various training environments developed for XR-based training. The training environments were developed for training and assessing the users in varying levels of complexities. They were developed after discussions with the expert surgeons regarding the level of complexity and resemblance with the actual surgical procedure. A brief discussion of each of the training environments follows.



LISS Assembly Module

Fracture Reduction Module

LISS Insertion Module

Screw Insertion Module

Position Training Module

Guide Removal Module

Figure 4.2. Views of the six modules of the VR based LISS plating training simulator

Training Environment	**Complexity**	**Platform**
Training Environment 1 (Plate Assembly)	Low	VR/MR
Training Environment 2 (Plate Insertion)	Medium	VR
Training Environment 3 (Dynamic Plate Compression)	High	VR/MR
Training Environment 4 (Lag Technique)	High	VR

Table 4.1. Training Environments, Complexity, and Platforms

Figure 4.3. Views of VR and MR based training environments and users interacting with the MR and VR based training environments

4.2.1 TRAINING ENVIRONMENT 1 (LOW COMPLEXITY)

Training Environment 1 was developed to train users in the first step of the condylar plating surgical procedure known as condylar plate assembly. In this environment, the users train in assembling the condylar plate and other components such as insertion handle, locking pin, nut, posts, and wire guide. The condylar plate is assembled before inserting it inside the patient's leg. A view of the training environment 1 for the VR platform is shown in Figure 4.4 and for the MR platform is shown in Figure 4.5.

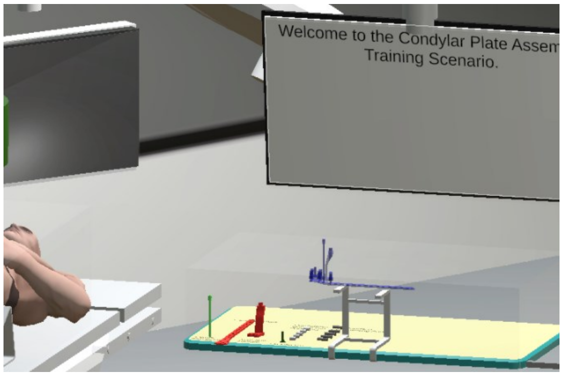


Figure 4.4. A view of Training environment 1 for VR platform

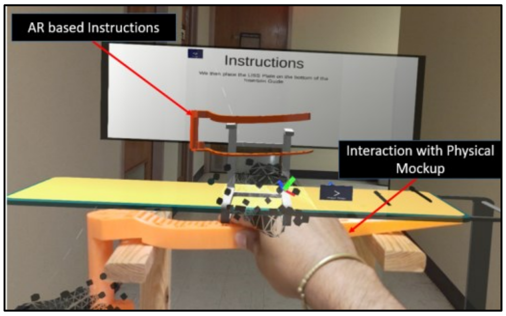


Figure 4.5. A view of Training environment 1 for MR platform

4.2.2 TRAINING ENVIRONMENT 2 (MODERATE COMPLEXITY)

The second training environment is developed for training users in the insertion and positioning of the condylar plate inside the patient's leg. The focus is on proper insertion of the plate following the ideal surgical path and avoiding crucial nerves during the insertion. The training also focuses on minimizing the non-essential hand movements during surgery. The training consists of three scenarios which are integrated within the VR-based environment. A view of the training environment 2 for the VR platform is shown in Figure 4.6.

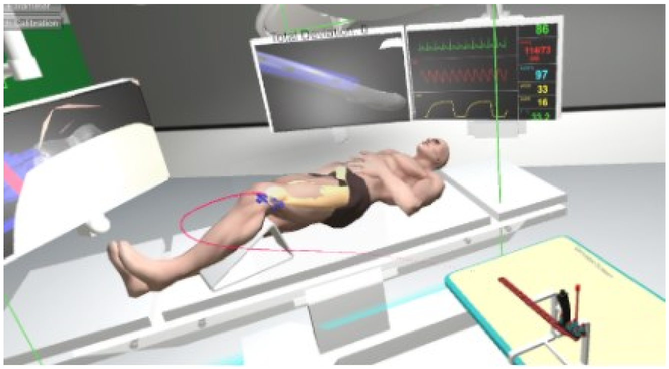


Figure 4.6. A view of Training environment 2 for the VR platform

The discussion of the three scenarios follows.

Scenario 1: Inserting the plate inside the patients' leg with minimal deviation from the ideal surgical path

The Vive based plate insertion environment provides the necessary information to the residents to determine the appropriate surgical pathway. Deviation from the appropriate pathway leads to inefficient hand movements and possible development of surgical bad habits. In other words, every movement of the hands should have a purpose to achieve a certain goal. The process of calculating the deviation for the path taken by the resident (user path) from the path specified by the (instructor / experienced) surgeon (correct path) is discussed in the assessment section.

Scenario 2: Avoiding the crucial neurovascular structures such as the Sciatic nerve during the insertion and positioning process

The sciatic nerve is the largest nerve in the body. It is formed by the union of five nerve roots from the lower spine. It is a crucial nerve that connects the spinal cord with the thigh, leg, and foot. It goes through the back of the knee and can be harmed while performing surgery in the region of the knee including condylar plating of the distal femur if proper care is not taken. In this scenario, the user holds the plate using the Vive controller and tries to position the plate correctly without going too close to the sciatic nerve.

Scenario 3: Minimizing the non-essential hand movements during the insertion and positioning process

The correct positioning of the condylar plate on the femur is the most critical step of the condylar plating surgical procedure. The surgeons need to be precise and accurate while inserting the condylar plate on the distal lateral side of the femur. Non-essential hand movements (NEHM) such as handshaking and wobbliness affect the surgeon’s ability to precisely and accurately insert the condylar plate. In this training scenario, the users learn to reduce the non-essential hand movements.

4.2.3 TRAINING ENVIRONMENT 3 (HIGH COMPLEXITY)

Dynamic Plate compression environment is one of the two complex training environments developed. 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 4.7 shows the view of the MR-based training environment 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.

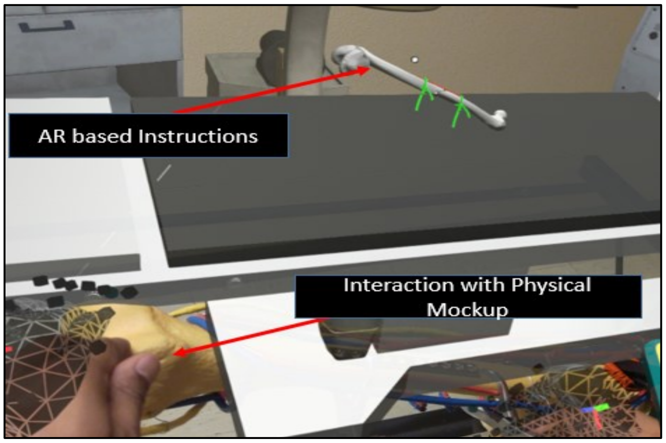


Figure 4.7. A view of Training environment 3 for MR platform

4.2.4 TRAINING ENVIRONMENT 4 (HIGH COMPLEXITY)

The fourth environment is developed to train users in a complicated scenario in which they have to perform lag technique along with the condylar plating surgical procedure. In certain fracture conditions, only performing condylar plating is not sufficient. The surgeons need to include any other related procedure to successfully complete the surgery. Lag technique is one such related surgical procedure. It is normally used to compress fractures together. In this training scenario, the users training in using lag technique concepts during the condylar plating procedure. The users train in multiple activities such as fracture reduction, drilling, and screwing in this complicated training scenario. A view of the training environment 4 for the VR platform is shown in Figure 4.8.

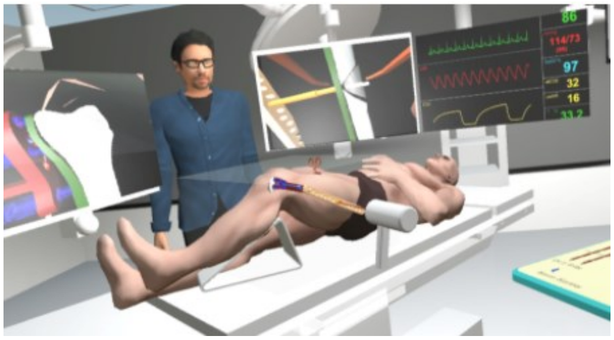


Figure 4.8. A view of Training environment 3 for VR platform

4.2.5 CHARACTERIZATION OF THE TRAINING ENVIRONMENTS

The design for XR based training environments needs to support characteristics such as affordance, visual density, interaction abilities, ability to communicate the objective of the training, distractions and cognitive load optimization, ability to convey to trainee the relationships of OOI in the target scene (functional and geometry/topology), the capability of helping the trainee become proficient in the target scenario or process.

A good design for the XR-based training environments can be defined as having high affordance, optimal visual density, minimal distractions, improving cognition at an optimal cognitive load with the help of a training avatar assisting in skills and knowledge acquisition.

In order to quantify the characteristics, any training environment can be described in the form of a tuple. The characteristics tuple (CT) consists of the following attributes or factors.

CT: <A, VD, CL, P, G, Q, I, T, TO, AS>

Where,

A is the Affordance which can be categorized as static, dynamic, and tactile affordance. A = {S, D, T}

VD is the visual density which can be categorized as high or low VD. VD = {HVD, LVD}

CL is the cognitive load imposed which can be categorized as cognitive load due to stress inducers, distractions, and repetition. CL = {SI, D, R}

P is the platform which can be Mixed Reality or Virtual Reality. P = {VR, MR}

G is the type of guidance provided such as 3D Avatar or Hand model. G = {A, H}

Q is the type of cue provided such as voice or text. Q = {V, T}

I is the level of immersion which can be categorized as non or fully immersive. I = {NI, FI}

T is the type of tactility such as non-tactile or tactile. T = {NT, T}

TO is the training objective of the training environment

AS is the assessment scenarios which can be categorized into comprehension, skills, knowledge, and cognitive load assessment. AS = {CA, KA, SA, CLA}

The characteristics tuple (CT) serves as a foundation for the creation of different variations of the XR environments. Further, the tuple also guides the development of assessment scenarios including the creation of the design of experiment tables presented in the latter part of this chapter.

4.2.6 COMPUTATIONAL APPROACHES

4.2.6.1 Penalty based A-Star Approach

There are several obstacles that surgeons need to consider during plate insertion. These obstacles can be instruments such as clamps, retractors, suction, hose, etc. Critical nerves, arteries, tumors can also act as obstacles during the fracture reduction process. Expert surgeons can correctly and consistently avoid such obstacles as they have the skill and experience in performing such tasks. However, such intricate movements may be difficult to perform for a medical resident. One of the training modules will specifically seek to provide such a much-needed experience while introducing residents to the 3D layout of such surgical scenarios. In this proposed module, a novel surgical guidance approach based on complex algorithms that will find the best obstacle-free path for the surgeon during surgery is discussed; such path planning can help residents and beginning surgeons to acquire experience in navigating the target surgical area by avoiding hitting crucial blood vessels and other instruments. Using this guidance system as part of the training, the residents are able to obtain experience interacting and completing various tasks following this automated path (where they will be guided by the training avatar and 3D path cues). After their training, their skills acquisition is assessed through 3D challenge tests.

The automated (computer-generated) path planner is designed based on the A-star algorithm; this algorithm has been used in other engineering contexts such as finding obstacle-free paths for robots during mechanical assembly, to determine flight paths of unmanned aerial vehicles (UAVs) around buildings in 3D space, among others [124, 125].

In the penalty-based A-star algorithm-based path planning approach for condylar plating, the surgery region (or target surgery area) is divided into a 3D grid consisting of n cells as shown in Fig. 4.9. Subsequently, the obstacles such as clamps, nerves, arteries among others are mapped on the 3D grid by rounding coordinates points to the nearest cell.

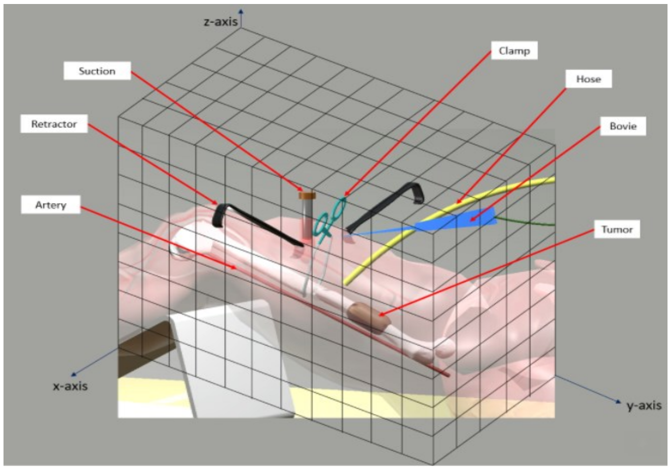


Figure 4.9. A Star based Path Planning for Orthopedic Surgery

This algorithm takes an input of the originating cell (from where the suturing begins) and the destination cell (where the suturing ends) to return a path that contains no obstacles. There are four cost variables (g, h, f, p) which are used to calculate the collision-free path.

- *g cost = cost of movement from starting point to the current cell on the grid*
- *h cost = estimated cost from the current cell to the destination cell*
- *p cost = additional cost imposed on the neighboring cells of the obstacles*

Each obstacle has been assigned a penalty based on the feedback from expert surgeons. The p-cost is only imposed on the neighboring cells of the obstacles. However, the p-cost for cells is set to zero. The pcost helps the users to generate a path which does not pass too close to the obstacles such as critical nerves and arteries.

$$f\ cost = g\ cost + h\ cost + p\ cost \qquad (1)$$

The f-cost is calculated for each cell and the optimal path is formed by following the cells for which the f-cost is minimum.

```
PENALTY BASED A-STAR ALGORITHM
Initialize Open/Closed List
Start Node → Open Node
While the open list is not empty
    Locate Node(N) with the smallest F-cost
    Remove Node(N) from the Open List
    Generate Neighbors of N
    For Each Neighbor
        If Neighbor → End Node, END
        Generate Nodes around Neighbor
        If Current Node neighbor → obstacle
            Add p. cost
        Else p.cost = 0
        Neighbor.g = N.g + Distance (Neighbor, N)
        Neighbor.h = Distance (Neighbor, End Node)
        Neighbor.f = Neighbor.g + Neighbor.h + p.cost
        If Neighbor.f < N.f
        Neighbor → Open Node
        N → Close Node
End While
```

Figure 4.10. Pseudocode for Penalty based A-Star Algorithm

4.2.6.2 Genetic Algorithm based Surgical Planning Approach

Condylar plating is a complex surgical procedure requiring a large number of implants and instruments. During, the surgery, implants, and instruments are kept in trays on two separate tables (implant table and equipment table, shown in Figure 4.11). A surgery technician picks up the implants and instruments placed in the trays and gives them to the surgeon (as shown in Figure 4.12) according to the surgical plan and procedure. Optimal positioning of trays on the table can lead to decreased movements of the technician leading to efficient surgery and saving crucial time which is of prime importance for the success of such complex surgeries.

In general, the GA is an evolutionary algorithm which 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 4.13.

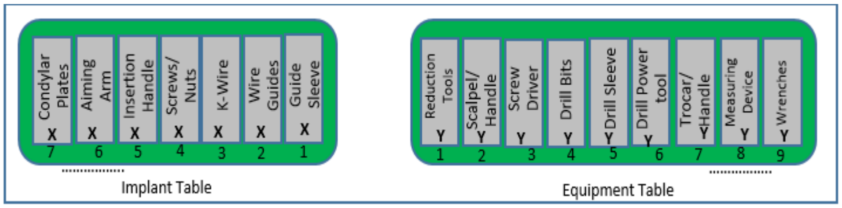


Figure 4.11. Implant and Equipment table for the Condylar Plating Surgical Procedure

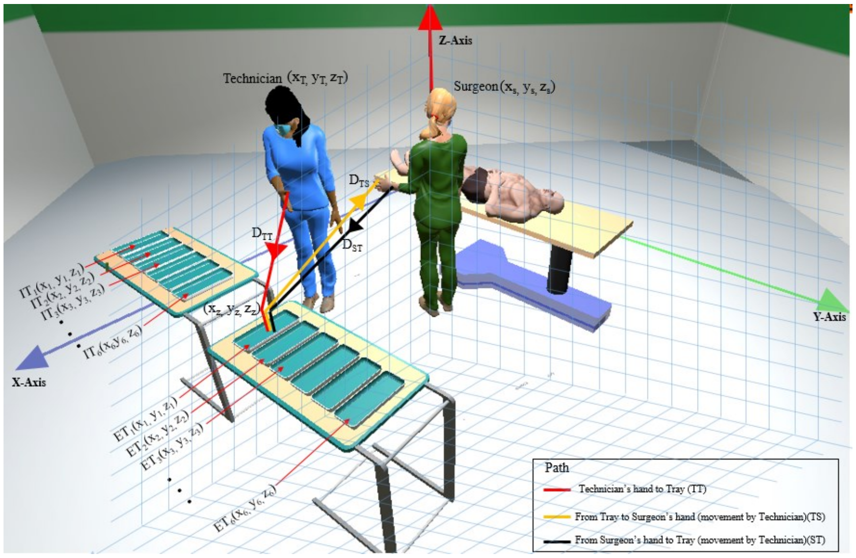
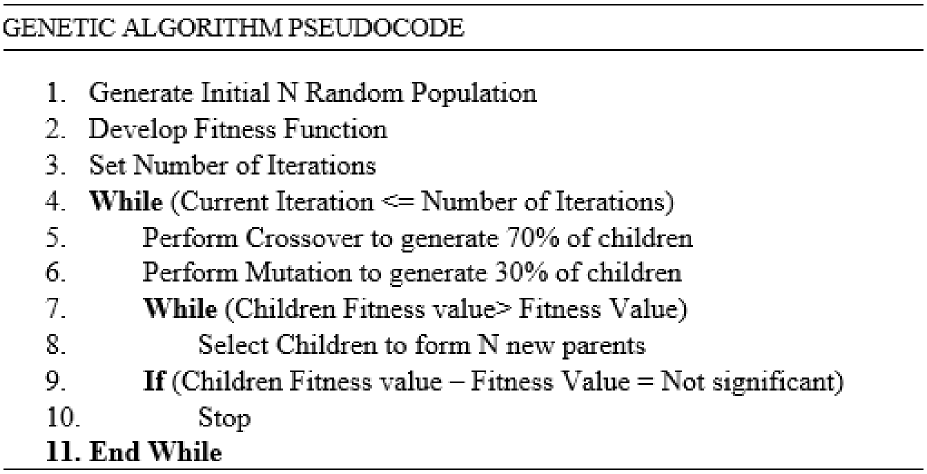


Figure 4.12. Layout showing the positions of trays, surgeon, and surgery technician

There are some constraints which 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.
- Since, some of the equipment and implants are needed multiple times, hence the surgery technician would visit some of the trays multiple times.

- 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

```
Generate Initial N Random Population
Develop Fitness Function
Set Number of Iterations
While (Current Iteration <= Number of Iterations)
    Perform Crossover to generate 70% of children
    Perform Mutation to generate 30% of children
    While (Children Fitness value> Fitness Value)
        Select Children to form N new parents
    If (Children Fitness value – Fitness Value = Not significant)
        Stop
End While
```

Figure 4.13. Pseudocode for Genetic Algorithm

4.3 HCI BASED DESIGN APPROACH

For the design of complex XR framework 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 [14]. In the context of designing cyber-human frameworks, 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 framework developed for orthopedic surgical training. The focus of the research is on studying the role of three HCI factors viz. Affordance, Visual density, and

Cognitive load during design, development, and evaluation of the framework. Apart from utilizing and modifying the currently accepted definitions of affordance, a detailed classification of affordance has also been presented in this research. Further, new measures such as dynamic and tactile affordance have also been described and implemented in this research.

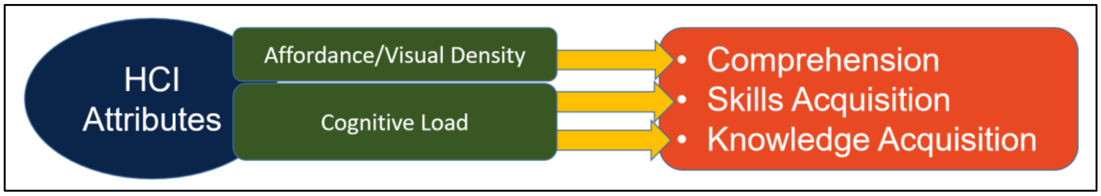


Figure 4.14. Impact of HCI based Attributes on Comprehension, Skills and Knowledge acquisition

4.3.1 AFFORDANCE

Affordance can be described as the action possibilities provided to the users in the environment. As described in chapter 2, researchers have not provided a proper classification of affordance. Traditionally affordance has been defined only in terms of visual and spatial understanding offer scene. The past researchers focused on how basic tasks such as passing through a door, an aperture, observing gaps affect affordance in virtual and augmented reality [86-91]. There has not been any 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 [91, 127, 128]. 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 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 4.15 shows the categorization of the affordance which was proposed in this research.

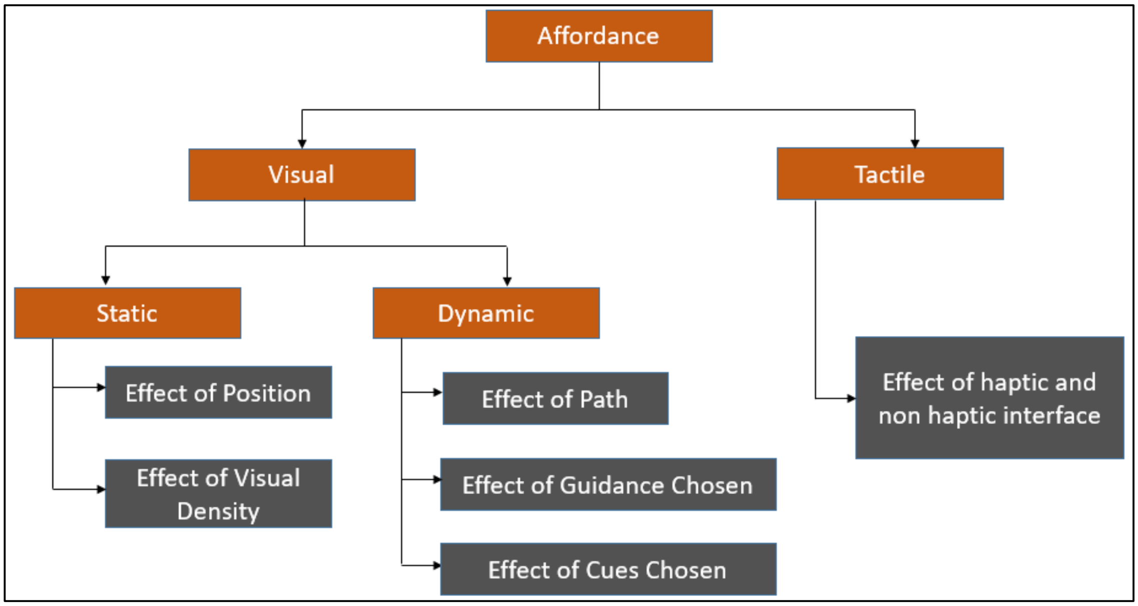


Figure 4.15. Categorization of Affordances

Before understanding the affordances of a scene, it is important to understand the target scene or the environment. Target scene can be defined by the cardinality of the scene as well as the complexity of the scene. Each scene can have a number of primary or secondary areas. Primary areas are the areas in the target scene (operation theatre, in our case) where the surgical procedure or related activities are being performed. Secondary areas are the areas which are the part of the operation theatre where the actual surgical procedures are not being performed. A cluster of primary or secondary areas is described as the primary or secondary region. A target scene is composed of a number of primary and secondary regions.

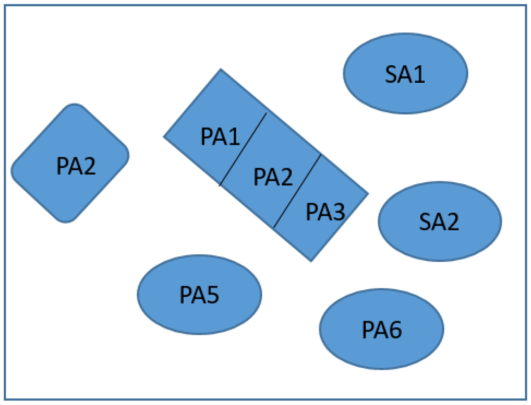


Figure 4.16. Primary and Secondary Areas of the Scene

$$C\ (TS) = C\ (PR) + C\ (SR)$$

Where,

$C\ (TS)$ = *Cardinality of Target Scene*

$C\ (PR)$ = *Cardinality of Primary Region*

$C\ (SR)$ = *Cardinality of Secondary Region*

$C(PR) = PA1 + PA2....Pan;\ n>1;$ *When* $n = 1,\ C(PR) = PA1$

$C(SR) = SA1 + SA2....SAn;\ n>1;$ *When* $n = 1,\ C(SR) = SA1$

Based on the number of primary (PAs) and secondary areas (SAs) and the number of objects in PA and SA; a scene can be defined as a low visual density (LVD) scene or a high visual density (HVD) scene. In an LVD scene, a fewer number of objects are included in a target area. An example of an LVD scene is shown in Figure 4.17. As seen in the figure, there are ‘n’ objects in one primary area (PA1); the lower number of objects in PA1 makes the scene in Figure 4.17 an LVD scene. In Figure 4.18, an example of an HVD scene is shown. A seen in the figure, there are a total of ‘n+N’ in one primary area (PA1). The higher number of objects in PA1 makes the scene in Figure 4.18 an HVD scene.

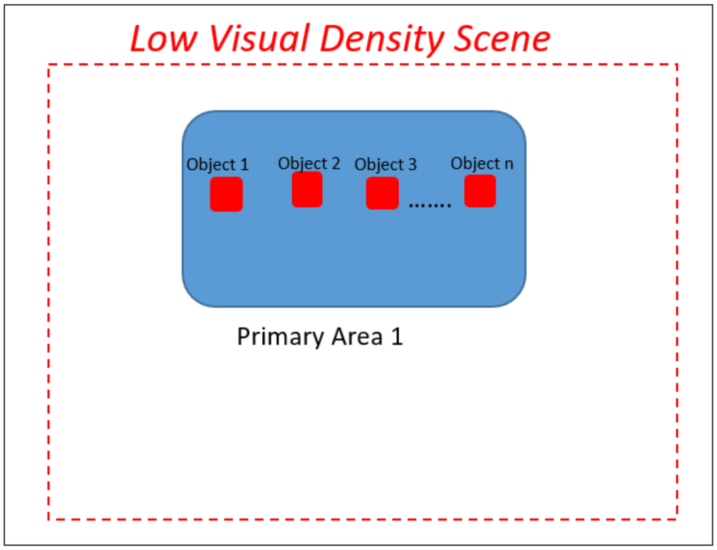


Figure 4.17. A view of a Low Visual Density (LVD) scene

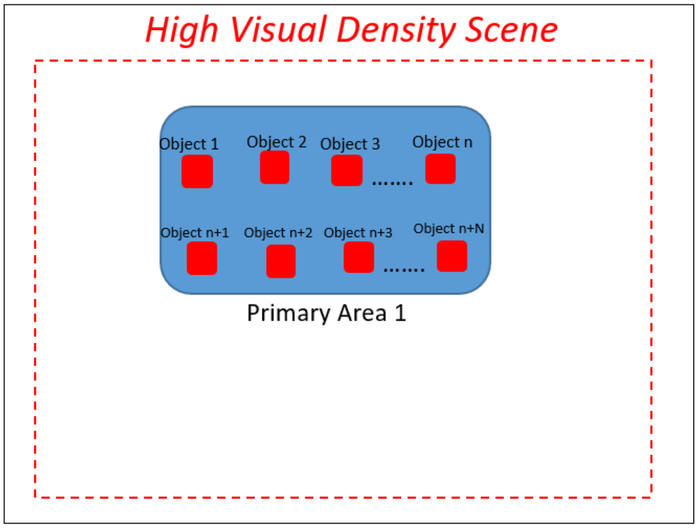


Figure 4.18. A view of a High Visual Density (LVD) scene

If there are an equal number of objects in two scenes; the number of primary and secondary areas can be used to define the visual density of the scene. As seen in Figures 4.19 and 4.20, there are N objects in both the scenes; however, there is only one primary area (PA1) in the scene shown in Figure 4.19, and objects are concentrated in a smaller area making it an HVD scene. In Figure 4.20, there are N objects as well but they are distributed over a larger area (Primary Area 1 and 2 (PA1 and PA2)) making it an LVD scene.

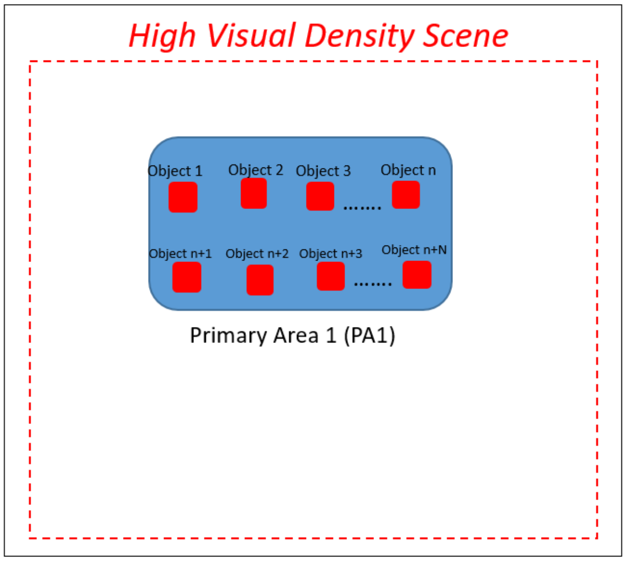


Figure 4.19. A view of a High Visual Density (LVD) scene based on the number of primary areas

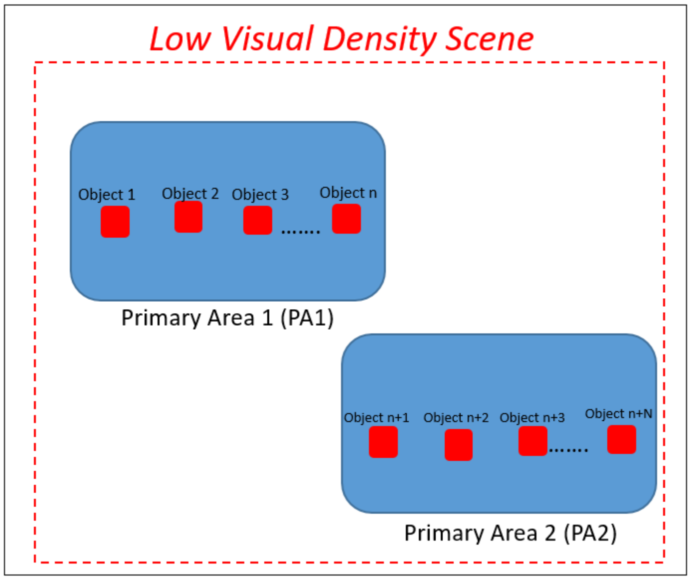


Figure 4.20. A view of a Low Visual Density (LVD) scene based on the number of primary areas

Plate insertion training environment was selected as the low visual density (LVD) environment. A view of the plate insertion training environment is shown in Figure 4.21. As seen in the figure, there are only two objects in the scene distributed over two primary areas. A lower number of objects over a larger area makes the plate insertion training environment an LVD scene. Plate assembly training environment was selected as the high visual density (HVD) environment. A total of fourteen objects are placed in one primary area in the plate assembly training environment making it an HVD scene. A view of the plate assembly environment is shown in Figure 4.22.

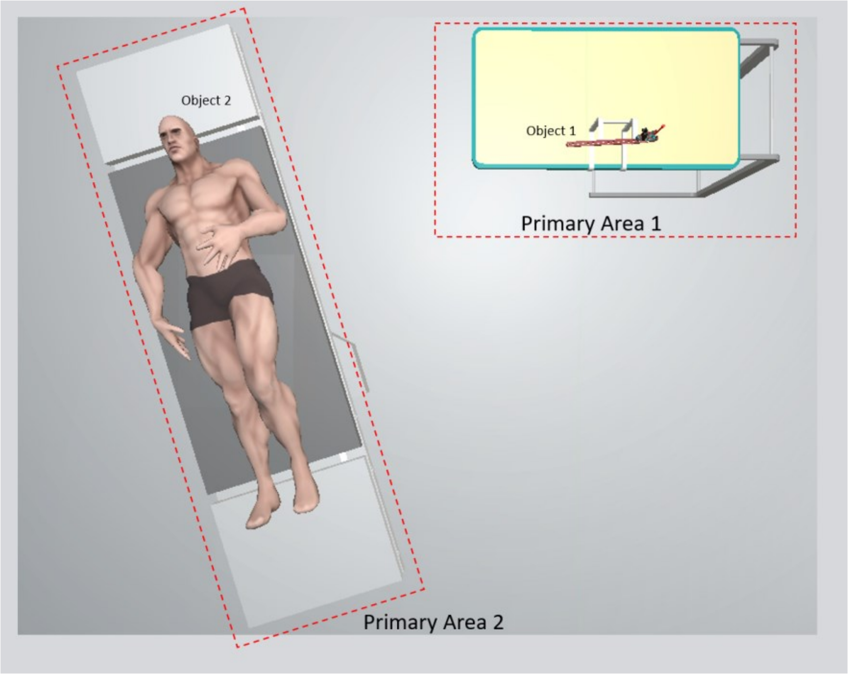


Figure 4.21. A view of the plate insertion training environment (Low Visual Density Scene)

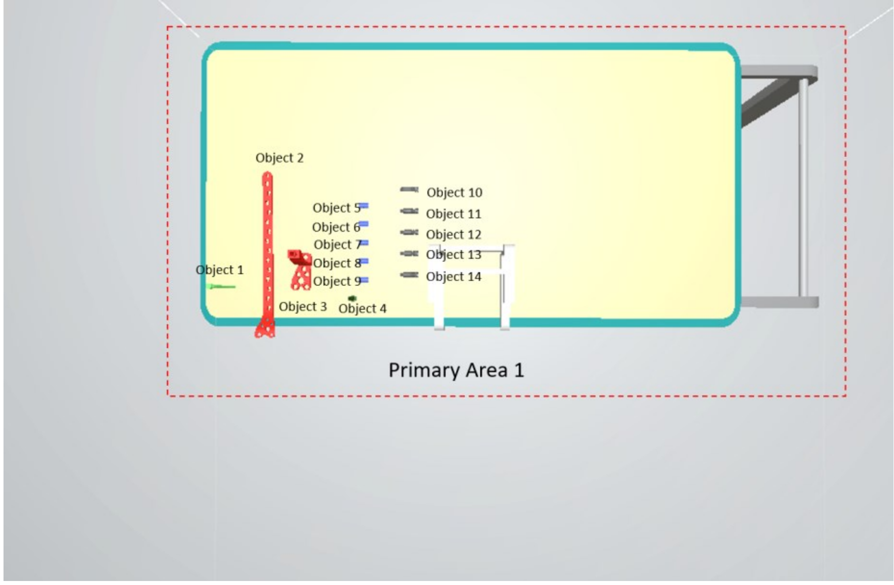


Figure 4.22. A view of plate assembly training environment (High Visual Density Scene)

The affordance related studies described in this research throw light on the comprehension and understanding of a target environment from various positions and perspectives as a user navigates or traverses along certain paths within that environment; this includes understanding relationships of objects of interest (OOI), which is key to the comprehension of interface menus, controls, and cues; these OOIs can be the virtual models of the operation theatre, patient, implants, and tools, patient table, table for tools, cabinets, lights, screens for x-ray images, screens of text cues, avatars, nurses and other surgeon's models, etc. Elaboration of different types of affordances is presented below.

4.3.1.1 Static Visual Affordance – Effect of Position (SVA –P)

Static visual affordance (SVA–P) is defined as a function of comprehension of a scene by a user inside a virtual 3D environment standing at a specific position P (within that target 3D environment) over a fixed period of time (T).

Comprehension (C) = f (P, T)

SVA-P <=>C

Two target scenes were developed for the SVA-P related study. The first scene involved a scalpel being used to make a cut on the patients' leg and the second scene involved inserting a clamp inside the patients' leg to hold the fractured bone in location.

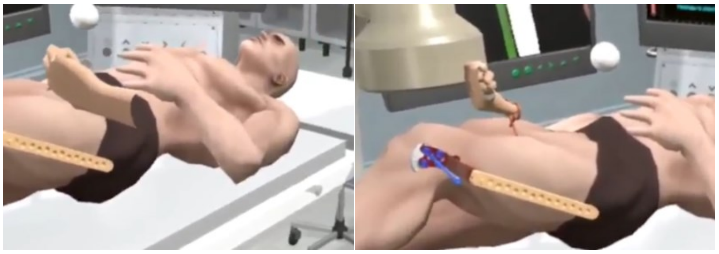


Figure 4.23. Target scenes for Static Visual Affordance Studies; view of the scene involving scalpel to make a cut (left) and view of the scene involving clamp to hold the fractured bone (right)

4.3.1.2 Static Visual Affordance – Effect of Visual Density (SVA –VD)

The visual density in a target scene is a measure of the number of objects/ cubic unit in a given layout. A user's understanding can be affected by the visual density and appearance/characteristics of the OOIs (color/contrast/lighting and textures). Static visual affordance (SVA–VD) can be defined as the function of comprehension (C) standing at a specific position (P) and observing a scene with specific visual density (VD) over a fixed period of time (T)

$$\text{Comprehension } (C) = f(P, VD, T)$$

$$SVA\text{-}VD <=> C$$

Two target scenes were developed for the SVA-VD related study. The first scene was a High Visual Density (HVD) scene consisting of 1 primary area and the second scene was a Low Visual Density (LVD) scene consisting of a primary region with two primary areas. Two positions were also assigned for the study (P1 and P2); P1 being close to the primary areas and P2 being further away from the primary areas as shown in Figures 4.21 and 4.22 .

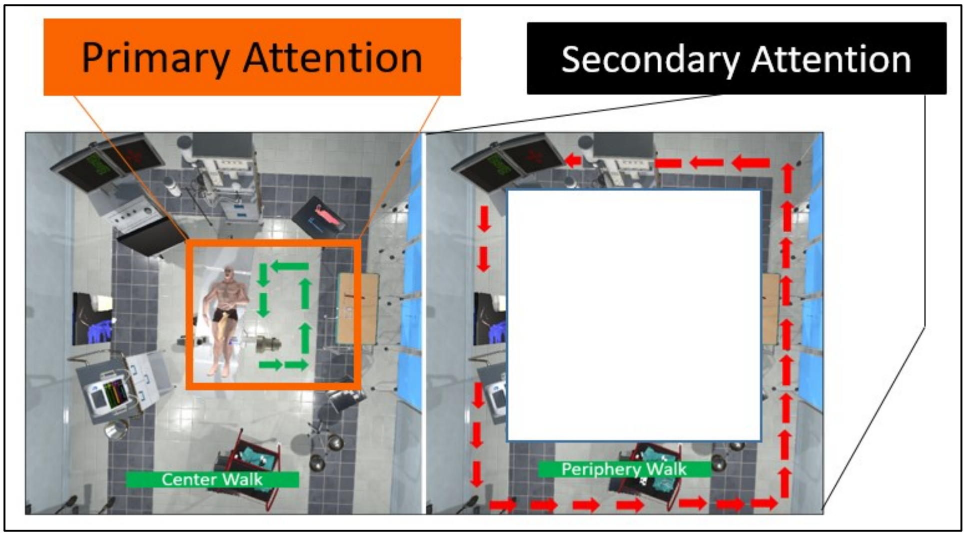
4.3.1.3 Dynamic Affordance – Effect of Path (DA –P)

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 4.24. The users could take a central path or a peripheral path while interacting with the target scene (Figure 4.24).



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

4.3.1.4 Dynamic Affordance – Effect of Guidance (DA–G)

Dynamic Affordance (DA –G) can be defined as a function of comprehension of a scene by a user who is provided certain guidance (G) during the interactions over a fixed period of time (T).

$$C = f(G, T)$$

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

Plate Assembly environment and Lag Technique environment (described in section 3.3) were utilized for the DA-G studies. Two types of guidance were used in the study. In the first type of guidance, an avatar model demonstrated the surgical procedure to the users and in the second type of environment, a hand model showed the surgical procedure. The two types of guidance used are shown in Figure 4.25.

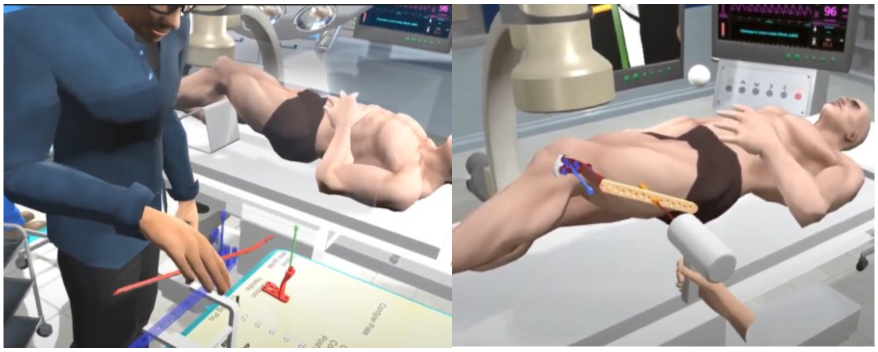


Figure 4.25. Types of Guidance; Avatar model (left) and Hand model (right)

4.3.1.5 Dynamic Affordance – Effect of Cues (DA–Q)

Dynamic Affordance (DA –Q) can be defined as a function of comprehension of a scene by a user who is provided a certain type of cue (Q) during the interactions over a fixed period of time (T).

$C = f(Q, T)$

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

Plate Insertion environment and Dynamic Plate Compression environment (described in section 3.2) were utilized for the DA-G studies. Two types of cues were used in the study. The first type of cue was the voice-based cue describing each step of the procedure and the second type of cue was the text-based presented on a whiteboard.

4.3.1.6 Tactile Affordance

Tactile Affordance (TA) can be defined as the function of a scene's ability to support comprehension through the sense of touch (TM) over a fixed period of time (T).

$C = f(TMi, \Delta T)$

$TM <=> C$

i = 1 = type of touch response (user feels tactile vibration through haptic interface)

i =2 = no tactile vibration

Plate Insertion environment and Dynamic Plate Compression environment (described in section 3.2) were utilized for the TA studies. The users were provided two types of interaction capabilities in this study. The users were able to use a haptic device which provided tactile vibration during the interaction in the first case. In the second case, the users interacted with the environment using the non-tactile Vive controller. The views of users interacting with the haptic device and vive controller are shown in Figure 4.26.

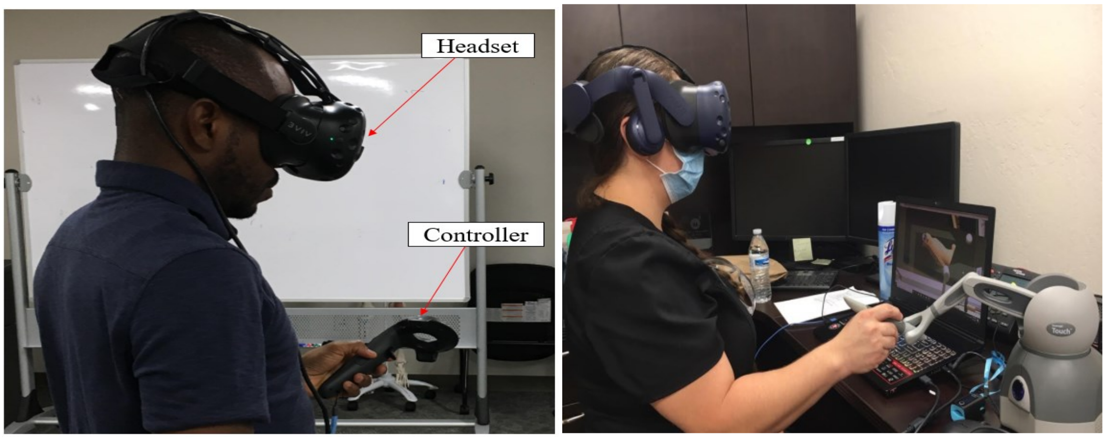


Figure 4.26. A user interacting with Vive controller (left) and haptic device (right)

4.3.2 COGNITIVE LOAD

In this research, the focus is on studying the relationship between users’ knowledge and skills acquisition and the cognitive functioning of a human. The working memory, in general, may vary across users; our plan is to design the environments for such varying user capabilities. If the complexity of a certain task is greater than a user’s cognitive load, it negatively affects the learning outcomes resulting in cognitive overload. Learning systems should be designed in a way that provides appropriate levels of cognitive load to their users. Cognitive load theory categorizes cognitive load into two broad types: intrinsic and extraneous load [16]. 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. Previous work on cognitive load mostly focused on assessing the load on the users using various subjective and objective assessment techniques [71, 72, 76-82]. Researchers have not focused on developing scenarios within the XR environments which would affect the load on the users. Few researchers have used dual-task measures depending on basic tasks such as buzzing sound, identifying letters, among others [73-75]. However, such tasks are completely unrelated to the process being performed in the XR environment. In the proposed framework, the tasks related to the process (surgical training) being performed in the XR environment are being used to measure the cognitive load on the users. Additional cognitive load was imposed on the users during the interactions with the training environments such as stress inducers and distractions. Stress inducers are additional cognitive load which are associated with the surgical procedure. Events such as deteriorating patient condition, errors leading to a life-threatening condition of the patient can be categorized as stress inducers. Distractions, on the other hand, are additional cognitive laod associated with external factors unrelated to the surgical procedures. Events such as a medical ambulance passing by, various alerts (bomb, fire, etc.), a nurse mistakenly entering the operating room, among others can be considered as distractions. Further, it was also studied whether repetition has any impact on the reduction of cognitive load on the users. An elaboration of the studies is presented below.

4.3.2.1 Cognitive Load – Effect of Stress Inducers

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 Lag Technique training environment (described in section 3.2). 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. Figure 4.27 shows a view of the two stress inducers implemented in the training scenario.

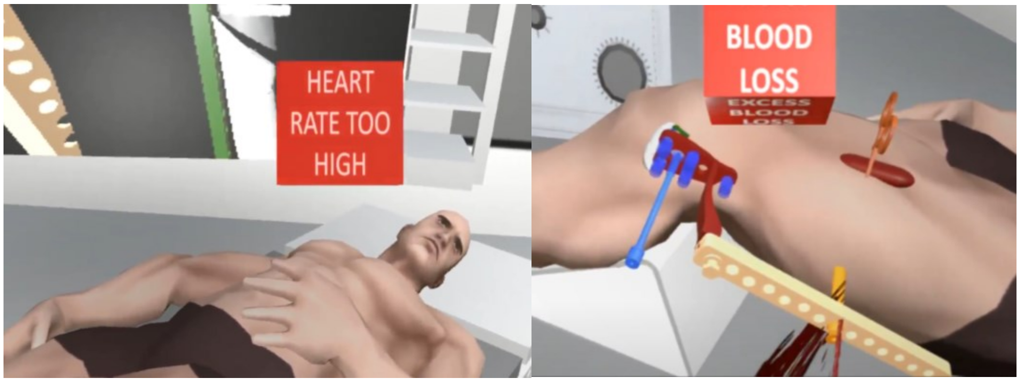


Figure 4.27. Stress Inducers introduced in the training environments; patient's vital sign increase (left) and blood hemorrhage (right)

4.3.2.2 Cognitive Load – Effect of Distractions

In real-life scenarios, the surgeons might face other distractions apart from the stress inducers related to patients. Such distractions might impact the surgeon's performance and the overall surgery. Distractions such as alarms beeping, lights blinking, the background noise of an ambulance, unauthorized persons entering the surgical room may happen in real life. In this research, we are trying to assess the impact of such distractions on users' knowledge and skills acquisition. The distractions were categorized into three groups which are shown in Table 4.2.

Type	**Distraction**
Audio	• Sirens • Ambulance sounds • Background sound of nurses

Visual	• Nurse walking in abruptly
	• Tables Falling
	• Lights blinking showing emergency code
	    • Red Light blinking (Fire)
	    • Black Light blinking (Bomb threat)
	    • Blue Light blinking (Cardiac arrest)
	    • Orange Light blinking (Hazardous materials)
	    • Green Light blinking (Violent behavior)

Audio-Visual	• Sirens • Ambulance sounds • Background sound of nurses • Nurse walking in abruptly • Tables Falling • Lights blinking

Table 4.2. Types of distractions

4.3.2.3 Cognitive Load – Effect of Repetition

It can be useful to understand how repetition affects the users' skills and knowledge acquisition to design and develop user-friendly and effective training environments. Another critical aspect necessary to be studied is how repetition affects the mental composure or cognitive capabilities of the users during interactions with the training environments. Two levels of repetition were included for the plate insertion training environment (discussed in section 3.3) viz. (a) high and (b) low.

a) High Repetition: The user interacted with the training environment five times before interacting with the challenge scenario.
b) Low Repetition: The user interacted with the training environment two times before interacting with the challenge scenario.

4.3.3 COMPARISON STUDIES

4.3.3.1 Comparison Studies – VR and MR

Mixed Reality (MR) and Virtual Reality (VR) have their pros and cons. VR is currently inexpensive whereas MR provides the user the ability to interact with physical tools and instruments. In this research, we have focused on understanding the usefulness of VR and MR in different scenarios with varying levels of complexity.

Two training environments were developed for both VR and MR platform to understand their impact on users' knowledge and skills acquisition. The first environment was a low complexity environment where users learned to assemble a condylar plate and the second environment was a high complexity environment where the users learned about dynamic plate compression. Both the environments have been discussed in section 3.2.

4.3.3.2 Comparison Studies – One Main Task and Multiple Sub Tasks

In this study, the focus was to understand the effect of performing one main task versus multiple small tasks leading to the main task. The plate insertion training environment was used to understand this effect. The plate insertion task is discussed in section 3.2. Before the main plate insertion task, the users can perform sub-tasks such as the task to reduce non-essential hand movement and the task to avoid critical nerves and arteries during insertion. A group of users only performed the main task and the other group performed the two sub-tasks before performing the main task for this study.

In the following sections, a discussion of the integrated assessment approach and the design of the experiment developed for each of the studies described in section 3.4. (affordance, cognitive load, and comparison study) is presented.

4.4 INTEGRATED ASSESSMENT APPROACH

In this research, an innovative integrated assessment method is proposed which is based on four perspectives: comprehension assessment, knowledge assessment, skills assessment, and an assessment of cognitive load. The proposed assessment approach is closely linked with the design of the XR environments. The HCI criteria used in the design of the XR-based environments such as affordance, visual density, and cognitive load are further utilized for the assessment approach. Moreover, based on the HCI principle of the iterative design approach, the results and feedback from assessment activities guide the modifications and improvement of the XR-based environments. The assessment method with integrated perspectives lays the foundation for a robust and balanced assessment of the XR simulation environment on improving the knowledge and skills of the users involved in the simulation-based training. Table 4.3 provides a brief description of the various assessment utilized for the studies described in section 4.3.

Study	Assessment Type
Affordance	• Comprehension Assessment • Subjective Surveys
Cognitive Load	• Skills and Knowledge Assessment • Cognitive Load Measurement • Subjective Surveys
Comparison Studies	• Skills and Knowledge Assessment • Subjective Surveys

Table 4.3. Types of Assessment associated with the Studies

4.4.1 COMPREHENSION ASSESSMENT

Comprehension assessment is performed to understand whether the users understand the functional relationship between various aspects of the target scene. The aspects can be various objects of interest (OOIs) in the scene or the various activities being performed in the scene. For this assessment, it is assumed that the users do not have any prior experience with the target surgical procedure. The focus is on how much the users understand just by observing and interacting with the scene or how much the scene helps the users to comprehend, which is the definition of affordance of the scene. Hence, comprehension assessment was used in affordance-related studies.

4.4.2 KNOWLEDGE ASSESSMENT

Questionnaire-based pre and post-test method was used to assess the knowledge gained by the users after the interactions with the XR-based environment. In this method, the users first take a pre-test in which their knowledge regarding the condylar plate surgical procedure is assessed through a set of questions. Subsequently, they interact with the XR-based simulator performing the training activities. Finally, the users take the post-test in which the same set of questions asked in the pre-test is asked again. The knowledge gained is calculated by the difference in the score of post-test and pre-test. The knowledge assessment is used for both cognitive load and comparison studies.

4.4.3 SKILLS ASSESSMENT

The users learn different skills in the four training environments discussed in section 3. 3. After the user completed the training, they completed the 4 challenge scenarios based on Training environments 1, 2, 3, and 4. No voice or text cues were provided during the challenge session.

Users could ask for a hint which would reduce their score. The hint-based scoring system was common for the four training environments and was calculated as the following.

Hint based Score = (Total no. of hints– no. of hints used)/Total no. of hints*100 (2)

Environment 2 and 4 were more complicated and had a specific scoring system apart from the hint-based scoring assessment.

a. Challenge Scenario 2 (for Training environment 2)

As discussed in training environment 2, there are three sub scenarios for challenge scenario 2. The score for each sub scenario and the calculation of the cumulative score for this scenario is discussed in the following section.

Scenario 1: Inserting the plate inside the patients' leg with minimal deviation from the ideal surgical path

Figure 4.28 shows a conceptual diagram showing the correct path and the user path for the positioning of a virtual part. The initial and final position of the part is also shown in Figure 4.28. Collision detection has been utilized to calculate the deviation. As seen in Figure 4.28, a number of colliders have been placed in between the initial and final positions of the part. The correct path is shown in black and the user path is shown in red in Figure 4.28. Whenever, the part passes through the colliders, the coordinate of the collision point is noted for both the correct and user paths. The distance between the collision point of the user path and the correct path is the preliminary deviation. The total deviation is calculated as the average of deviations from the collision points on each of the colliders. The process of calculation of deviation follows.

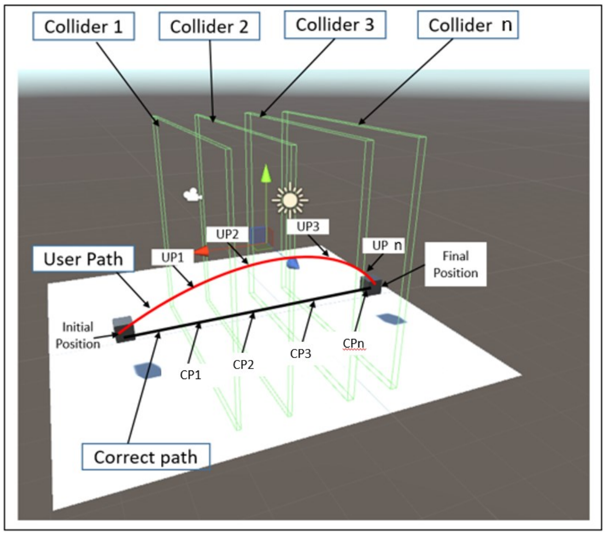


Figure 4.28. A conceptual diagram for calculation of deviation from the actual path

In Figure 4.28,

CP1, CP2, CP3,… CPn = correct path point; the point where the part hits the collider when it is moving in the correct path

UP1, UP2, UP3,… UPn = user path point; the point where the part hits the collider when the user is moving the part

Here,

Deviation 1 (D_1) = Distance between UP_1 and CP_1

Deviation 2 (D_2) = Distance between UP_2 and CP_2

………………………………………………

………………………………………………

Deviation n (D_n) = Distance between UP_n and CP_n

Hence,

Total Deviation (D)= $\sum_{i=1}^{n} \frac{D_i}{n}$

The final score (τ1) is calculated as

τ1 = (α1– D) * 100

where α1 is the initial score of the user and was set to 1 after discussions with the expert surgeons.

Scenario 2: Avoiding the crucial neurovascular structures such as Sciatic nerve during the insertion and positioning process

The position training environment consists of a virtual sciatic nerve which is placed below the femur bone of the virtual patient. A yellow/red light indicator is placed in the virtual environment as well. When the user is close to the sciatic nerve, the yellow light flashes; which is a warning provided to the user to change the trajectory of the condylar plate so that it does not hit the sciatic nerve. However, if the user hits the sciatic nerve, the red light flashes and the user has to restart the insertion and positioning procedure from the beginning. The environment also records the number of times the user went close to the sciatic nerve during the insertion and positioning procedure. The user's score is based on the number of times he/she went close to the sciatic nerve. The score is calculated as follows

α2 is the initial score of the user

β2 is the number of times the user goes close to the sciatic nerve

The final score (τ2) is calculated as

τ2 = α2 – β2

where α2 was set to 100 after discussions with the expert surgeons.

This scenario initiates when the user has completed the insertion of the assembled plate inside the patient's leg. In this scenario, the user holds the plate using the Vive controller and tries to position the plate correctly without going too close to the sciatic nerve.

Scenario 3: Minimizing the non-essential hand movements during the insertion and positioning process

In order to assess the users in minimizing the non-essential hand movements, the entire insertion region for the condylar plate is divided into three zones which are green, yellow, and red zones. The green zone is the acceptable region for the insertion. The user needs to move the cube in the green region from left to right. The yellow region and the red region are the regions the user should avoid. The users who tend to have non-essential hand movements are more likely to go to the yellow and red region moving the cube over the green zone. A real-time textual prompt-based training system is introduced so that the condylar plate remains in the green zone.

Here,

$\alpha3$ is the initial score of the user (time spent by the user in the green zone)

$\beta3$ is the time spent by the user in the yellow zone

σ is the penalty for spending time in the yellow zone

$\gamma3$ is the time spent by the user in the red zone

ω is the penalty for spending time in the red zone

The final score ($\tau3$) is calculated as

$$\tau3 = (\alpha3-\beta3*\sigma-\gamma3*\omega) * 100/ \alpha3$$

where σ and ω were set to 25 and 50 respectively after discussions with the expert surgeons.

The total score (cumulative score) for the Training environment is based on the following calculations: After the calculation of the total scores (τ1, τ2, and τ3)) for each of the three scenarios, the expert surgeons rated each scenario based on the impact it has on the training procedure (Table 4.4).

Scenarios	S1	S2	S3	S4	AWS
Inserting the plate inside the patients' leg with minimal deviation from the ideal surgical path.	30	50	35	15	32.5 (w1)
Avoiding the crucial nerves such as Sciatic nerve during the insertion and positioning process	50	30	35	60	43.75 (w2)
Minimizing the non-essential hand movements during the insertion and positioning process	20	20	30	25	23.75 (w3)

Table 4.4. Average Weighted Scores for Each Scenario

Here,

w1 is the weight for scenario 1 (Minimum deviation from the surgical pathway)

w2 is the weight for scenario 2 (proximity to the sciatic nerve)

w3 is the weight for scenario 3 (non-essential hand movement)

The cumulative score (weighted average) is

Cumulative Score (τ) = ((τ1*w1+ τ2*w2+ τ3*w3)/(w1+w2+w3))

b. Challenge Scenario 3

For all the other steps in this challenge scenario, hint-based scoring was used except for the drilling which is a crucial step in this training environment. The users were asked to drill the bone marked with yellow and red zone using the haptic device. The yellow light warns the user when he/she is too close to the no-go zone, The Red Light flashes when the user enters the no-go zone. The score calculation follows.

α is the initial score of the user

β is the number of times the user goes close to the no-go zone

The final score (τ) is calculated as

$\tau = \alpha - \beta$

where α was set to 100 after discussions with the expert surgeons

Final score = (final score + hint based score)/2

4.4.4 COGNITIVE LOAD MEASUREMENT

The measurement of cognitive responses of surgical residents provides a preliminary assessment of their ability to perform complex tasks under stress. In order to measure the cognitive load or mental stress, the pupil dilation and the heartbeat of the user are measured. It has been asserted that the increase in cognitive load or mental stress increases the dilation of pupil and heartbeat of the user. The pupil dilation is measured by using the eye tracker attached to the Vive Pro Eye immersive headset and the heartbeat was measured using a pulse oximeter. A view of the Vive Pro showing the eye trackers and a pulse oximeter is shown in Figure 4.29.

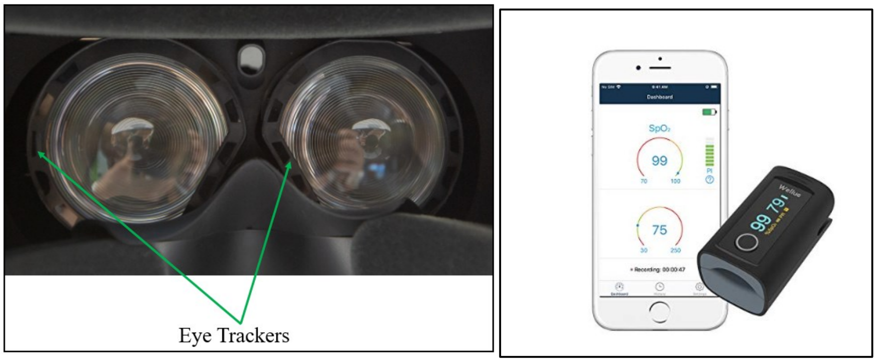


Figure 4.29. View of Eye Trackers in the Vive Pro headset (left) and Pulse oximeter used to measure the heartbeat of the participants (right)

4.4.5 SUBJECTIVE SURVEYS

Apart from the skills and knowledge assessments, Qualitative Feedback Surveys (QFS) were also conducted in which the participants provided qualitative responses related to the simulator. Each survey's response involved assigning a rating of 1 to 10 (with 1 being the lowest rating to 10 being the highest). Some of these criteria focused on providing feedback for user-friendliness and effectiveness of instruction support during the simulator-based training activities (number 1-6 in Table 3.5). Some of these criteria (numbers 7-12 in Table 3.5) were based on NASA Task Load Index (TLX) [71]. NASA TLX is considered one of the leading standards for measuring subjective workload for users across a wide range of applications; it has been used to collect user feedback on various environments such as simulators, aircraft cockpits; command, control, and communication (C3) workstations and laboratory environments.

No.	Feedback Criteria: Rate the following (10: Best, 1: Worst)
1.	User-friendliness of the user interface of the menu buttons and other interfaces
2.	The degree of usefulness of the controller
3.	a. The degree of usability of the simulator (in general).
4.	The degree of usefulness of the text-based interactions.
5.	The degree of usefulness of the 3D Avatar interaction during the training.
6.	The ease of navigating through the simulation environment.
7.	Performance: How do you think you performed?
8.	Effort: How hard did you have to focus in order to complete the training? (1: Low, 10: High)
9.	Frustration: How frustrated were you when trying to complete the surgical steps in the training? (1: Not frustrated, 10: Very frustrated)
10	Mental Demand: How mentally demanding was the training? (1: Not demanding, 10: Very demanding)
11	Physical Demand: How physically demanding was the training? (1: Not demanding, 10: Very demanding)
12	Temporal Demand: How hurried or rushed were you during training? (1: Not rushed, 10: Very rushed)

Table 3.5. Modified NASA TLX Survey

4.5 DESIGN OF EXPERIMENT

Design of experiment (DoE) is a method in which the relationship between various factors affecting the process is studied systematically [129]. DoE deals with planning, conducting, and analyzing experimental studies. In this section, DoE tables consisting of the studies presented in section 3.4 and independent variables, levels of the independent variables, and the dependent variables are presented.

Experiment	**Factor (Independent Variable)**	**Level**	**Response Variable (Dependent Variable)**
Static Visual Affordance	Position	Specified Position (Control group)	Comprehension
		User Chosen Position	
Static Visual Affordance – Effect of Visual Density	Visual Density	Low	Comprehension
		High	
	Position	Position 1	
		Position 2	
Dynamic Visual Affordance – Effect of Path	Path	Center Walk	Comprehension – Primary Attention
		Peripheral Walk	Comprehension – Secondary Attention
Dynamic Visual Affordance – Effect of Guidance	Guidance Model	Avatar	Comprehension
		Hand Model	
Dynamic Visual Affordance – Effect of Cues	Instruction Cues	Voice	Comprehension
		Text	
Tactile Affordance	Tactility	Vive based controller	Comprehension
		Haptic device	

Table 3.6. Design of Experiment Table for Affordance Studies

Experiment	**Factor (Independent Variable)**	**Level**	**Response Variable (Dependent Variable)**
Cognitive Load – Effect of Stressors	Stressor inducers	No Stress inducers	Knowledge
		Stress inducers	Skills
Cognitive Load – Effect of Distractions	Distractions	No distractions	Knowledge
		Audio	
		Visual	Skills
		Audio-visual	
Cognitive Load – Effect of Repetition	Repetition	Low (2)	Skills
		High (5)	

Table 3.7. Design of Experiment Table for Cognitive Load Studies

Experiment	**Factor (Independent Variable)**	**Level**	**Response Variable (Dependent Variable)**
Comparison – MR and VR	Platform	MR	Knowledge
		VR	Skills
Comparison – Main Task and Sub Tasks	Type of Task	Main Task	Skills
		Sub Tasks	Knowledge

Table 3.8. Design of Experiment Table for Comparison Studies

4.6 NEXT GENERATION NETWORKING

For the On-Line training activities, Next Generation Internet technologies have been implemented to allow residents and users to access the simulator 24/7 from various locations. While the current Internet has become ubiquitous in supporting novel societal and commercial usages, it was never originally designed for such a wide range of applications [130]. The incremental solutions used to address these concerns can be viewed as short-term 'patches'; further, the range of applications has necessitated hundreds of additional protocols and extensions, which make its management more and more complex. It has also posed demanding technological and policy challenges in security, mobility, heterogeneity, and complexity [131]. For these reasons, several initiatives have started the development of the Next Internet in the US, Europe [133], Japan, and other countries [133]. In the US, the Global Environment for Network Innovations (GENI) [132, 133] is an initiative led by the National Science Foundation that focuses on the design of the Next Generation Internet frameworks based on advanced networking characteristics which include multi-gigabit bandwidth, low latency, software-defined networking and/or control over the geographic location of resources.

To support this On-Line training approach, the surgical training application has been built on top of a 3D Virtual Reality engine called Unity. The Unity engine used in the simulator is a popular and easy-to-use platform for simulation and other gaming applications. Figure 4.30 shows the multi-participant architecture in Unity. Simulation Server (SS) in Figure 4.30 refers to the meeting place that puts simulation instances in touch with the Simulation Clients (SC) who wants to connect with it. As the Unity-based architecture is susceptible to single point failure of the SS, if the SS fails and/or if the network connection to the SS fails, the entire system fails and all SCs are deregistered and disconnected. This may be acceptable in the context of other multi-participant applications, but it is not acceptable in the surgery context given the sensitive nature of the surgical training application.

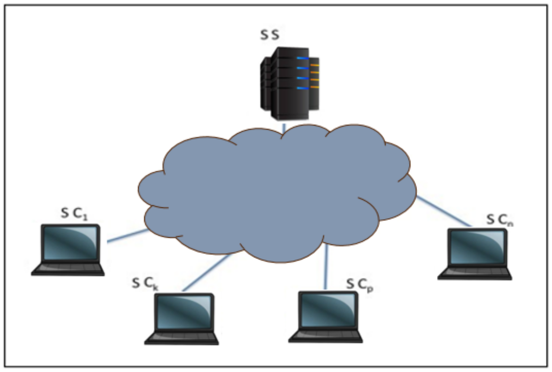


Figure 4.30. Multi participant simulation architecture in Unity (SS is the simulation server, and SCs are the simulation clients)

In the surgical application context, the participants are the trainees (students and residents). They can be also referred to as Tele-Medicine Clients (TMCs). Since Unity is not an open-source platform, it is not possible to modify its libraries to support resiliency against connection failures to the Tele-Medicine Server (TMS). As such support is important in telemedicine applications, Software Defined Networking (SDN) principles have been used to increase resiliency to TMS failures. SDN separates network control and forwarding function which enables network control to be directly programmable which makes it ideal for today’s dynamic and high bandwidth applications. Some of the benefits of SDN are that it is directly programmable, agile, centrally managed, open standards-based, and vendor-neutral [134].

Figure 4.31 shows the SDN-integrated architecture of our surgical application. There are r redundant TMSs in this architecture. Failure to connect to up to r-1 TMS can be seamlessly tolerated in this networked architecture. To achieve this, the TMCs do not connect directly to a TMS. Instead, each TMC connects to the TMSs through proxies implemented by SDN switches (realized through OpenFlow); OpenFlow is an SDN standard which allows network controllers to decide the network path packets across the network of switches. If there are m Open Flow Proxies (OFPs), then the TMCs are partitioned into m groups, and each group connects to the

TMSs through one of the OFPs. The OFPs play a crucial role in providing failure resiliency without introducing much latency.

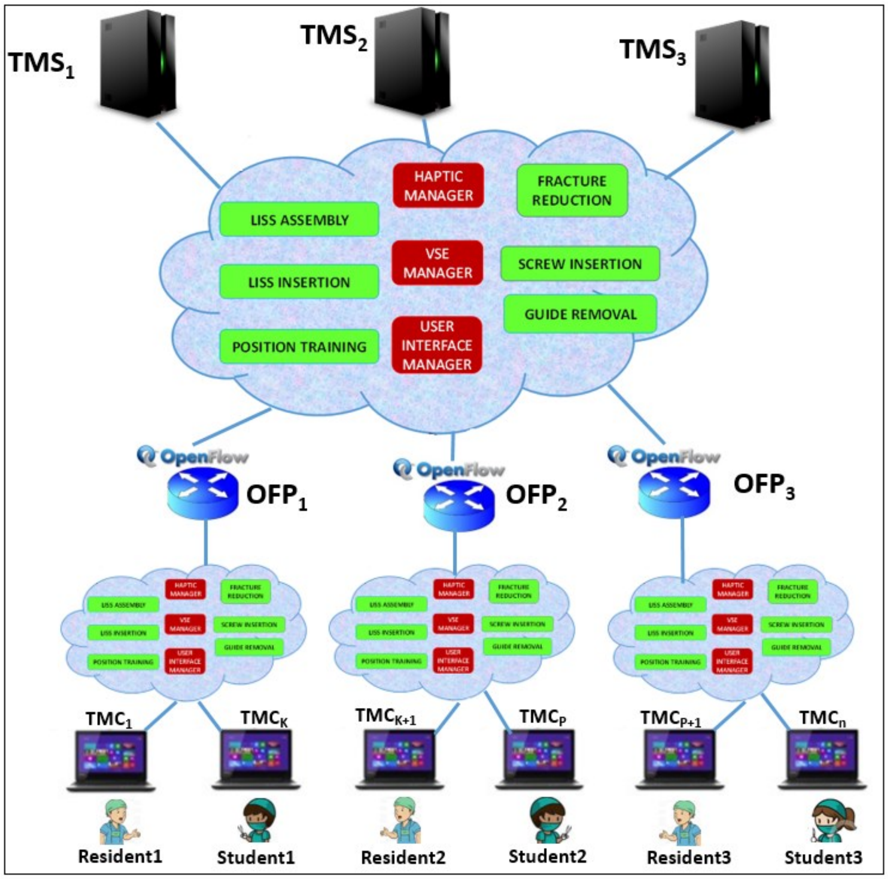


Figure 4.31. Architecture for the telemedicine surgical application (TMS is the telemedicine server, TMCs are telemedicine clients, and OFPs are OpenFlow switch-based proxies)

4.7 CONCLUSION

In this chapter, a detailed discussion of the HCI-based framework developed for the creation of XR-based surgical training environments was presented. Further, an elaboration of the components of the framework such as HCI-based design criteria, XR-based training environments, integrated assessment approach, and next generation networking was also presented. The design of experiment tables for the experiments showcased in the next chapter (Chapter 4) were also presented in this chapter.

CHAPTER V

OVERVIEW OF ASSESSMENT ACTIVITIES

5.1 INTRODUCTION

The overview of the assessment studies performed at multiple medical universities is presented in this chapter. The statistical analysis, findings, and observations from the results are also discussed. In section 5.2, the summary of the experiments discussed in Chapter 4 is presented again. In section 5.3, an elaboration of the dataset collected after the experiments is provided. The technical description of the statistical tests is provided in Section 5.4.

5.2 SUMMARY OF THE EXPERIMENTS

The experiments were categorized into three studies: affordance studies, cognitive load studies, and comparison studies. Figure 5.1 shows the experiments illustrated in a tree diagram. Further, tables 5.1, 5.2, and 5.3 provide a more detailed description of the experiments showing the name, the aim, the finding, and the statistical test used.

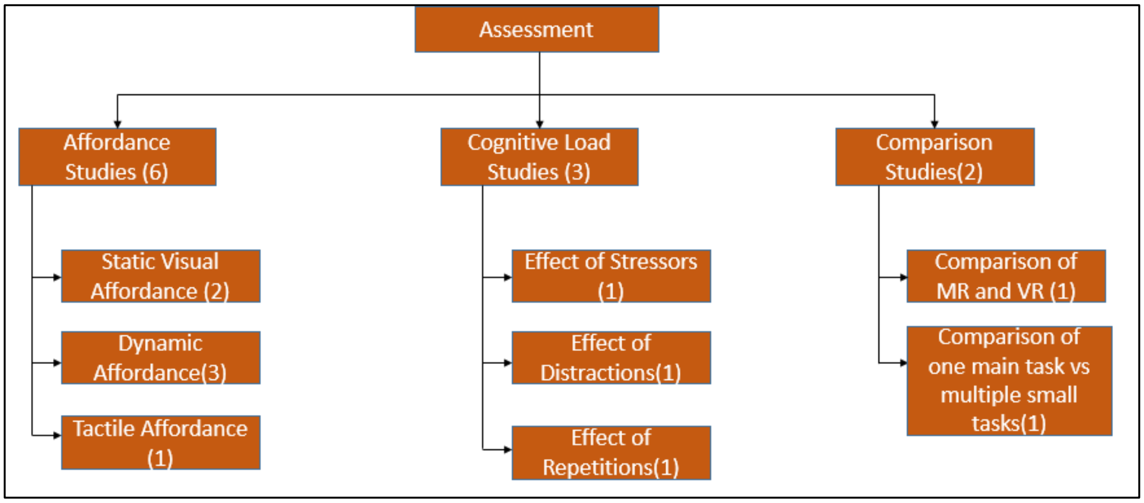


Figure 5.1. Experiments for Affordance, Cognitive Load and Comparison Studies

Experiment Name	**Aim**	**Statistical test**	**Finding**
Static Visual Affordance – Effect of Position	Understand the effect of Position on Affordance	T-test	No effect of position
Static Visual Affordance – Effect of Visual Density	Understand the effect of Visual Density and Position on Affordance	T-test	Statistically Significant effect of Position and Visual Density
Dynamic Visual Affordance – Effect of Path	Understand the effect of Path on Affordance	T-test	Statistically Significant effect of Path
Dynamic Visual Affordance – Effect of Guidance	Understand the effect of Guidance on Affordance	T-test	Statistically Significant effect of Guidance
Dynamic Visual Affordance – Effect of Cues	Understand the effect of Cues on Affordance	T-test	No significant effect for low complexity environment Statistically Significant effect for high complexity environment
Tactile Affordance	Understand the effect of tactile interface on Affordance	T-test	Statistically Significant effect of tactile interface

Table 5.2. Summary of experiments for Affordance Studies

Experiment Name	Aim	Statistical test	Finding
Cognitive Load – Effect of Stressors	Understand the effect of stress inducers on skills and knowledge acquisition	T-test	Statistically Significant effect of Stress Inducers
Cognitive Load – Effect of Distractions	Understand the effect of distractions on skills and knowledge acquisition	ANOVA	Statistically Significant effect on Skills acquisition No significant effect on knowledge acquisition
Cognitive Load – Effect of Repetition	Understand the effect of repetition on skills and knowledge acquisition	T-test	Statistically Significant effect of Repetition

Table 5.2. Summary of experiments for Cognitive Load Studies

Experiment Name	Aim	Statistical test	Finding
Comparison – MR and VR	Understand the effect of the platform (VR and MR) on skills and knowledge acquisition	T-test	No significant effect for low complexity environment Statistically Significant effect for high complexity environment
Comparison – Main Task and Sub Tasks	Understand the effect of main task and sub-tasks on skills and knowledge acquisition	T-test	Statistically Significant effect on Skills acquisition No significant effect on knowledge acquisition

Table 5.3. Summary of experiments for Comparison Studies

5.3 DATASET

Before the assessment activities, the three expert surgeons reviewed the training and assessment environments to ensure their correctness. They provided detailed feedback and a list of changes to be incorporated to create effective and user-friendly training and assessment environments. After these changes were implemented and verified, the immersive simulator-based assessment involving medical personnel was conducted.

5.3.1 DATASET COLLECTION

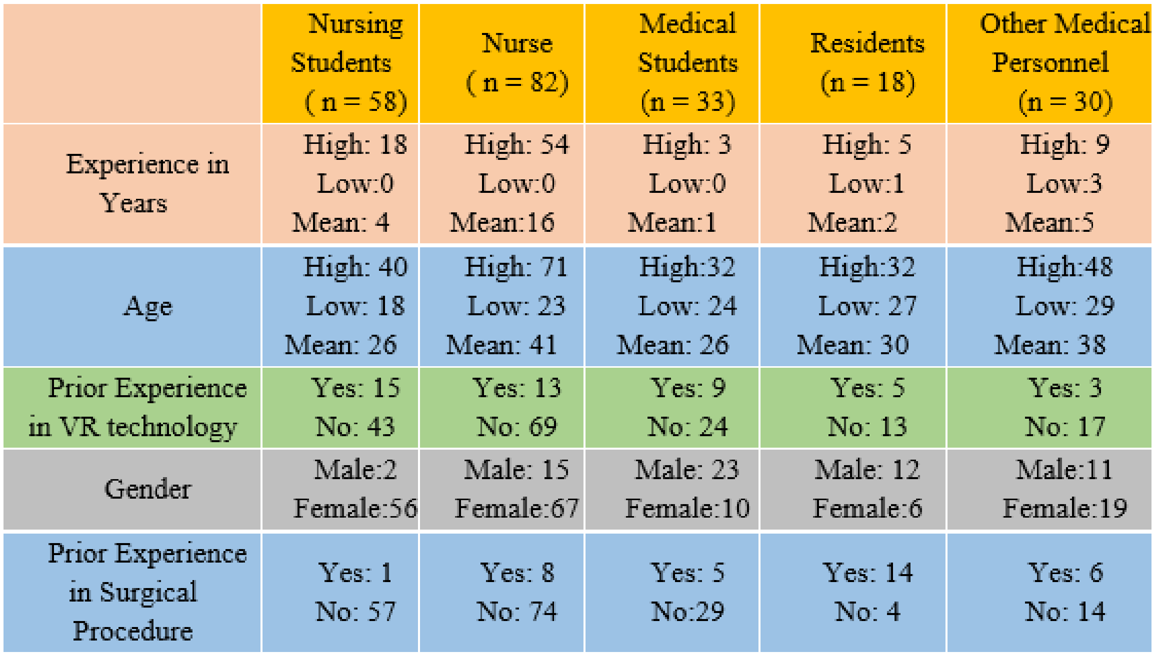
The expert orthopedic surgeon who has been advising on the design and development process also helped in conducting the assessment activities. The assessment activities were conducted at the following medical centers and universities to collect the dataset:

- Texas Tech University Health Sciences Center
- Dignity Regional Medical Center, Chandler
- Yavapai Regional Medical Center, Prescott Valley
- Northern Oklahoma College, Stillwater, Tonkawa, Enid
- Northwestern Oklahoma State University, Enid
- MD Anderson Cancer Center, Houston

The participants from the Texas Tech University Health Sciences Center and Burrell College of Osteopathic Medicine only participated in the knowledge assessment as the other assessments such as the skills assessments and HCI-based assessments were not fully designed yet. The participants from Texas Tech University Health Sciences Center and Burrell College of Osteopathic Medicine were medical students and residents. The participants from Dignity Regional Medical Center, Yavapai Regional Medical Center, Northern Oklahoma College, Northwestern Oklahoma State University, and MD Anderson Cancer Center participated in the comprehension assessment (for affordance studies), and skills and knowledge assessments (for the cognitive load and comparison studies). The participants from Dignity Regional Medical Center, Yavapai Regional Medical Center, and MD Anderson Cancer Center were practicing nurses whereas the participants from Northern Oklahoma College and Northwestern Oklahoma State University were nursing students.

5.3.2 DATASET DESCRIPTIVE SUMMARY

A total of 221 participants interacted with the XR-based simulator as part of the immersive simulator-based assessment studies. The demographics and the descriptive summary of the participants are provided in Table 5.4. There were a total of 221 participants who interacted with the simulators for the 13 studies. For each study, 80 participants interacted with the simulators. This was possible as a number of XR-based environments were developed for each study. For the affordance-related studies, a total of four environments were developed (2 for static affordance and 2 for dynamic affordance). Some of the training environments (discussed in Chapter 4) were also utilized for affordance studies (effect of visual density, the effect of avatar, and effect of tactile affordance). For the cognitive load and comparison studies, the four training environments (discussed in Chapter 4) were used. Some of the data points were used in more than one study which made it possible to include 80 participants for each study with only 221 participants.



	Nursing Students (n = 58)	Nurse (n = 82)	Medical Students (n = 33)	Residents (n = 18)	Other Medical Personnel (n = 30)
Experience in Years	High: 18 Low:0 Mean: 4	High: 54 Low:0 Mean:16	High: 3 Low:0 Mean:1	High: 5 Low:1 Mean:2	High: 9 Low:3 Mean:5
Age	High: 40 Low: 18 Mean: 26	High: 71 Low: 23 Mean: 41	High:32 Low: 24 Mean: 26	High:32 Low: 27 Mean: 30	High:48 Low: 29 Mean: 38
Prior Experience in VR technology	Yes: 15 No: 43	Yes: 13 No: 69	Yes: 9 No: 24	Yes: 5 No: 13	Yes: 3 No: 17
Gender	Male:2 Female:56	Male: 15 Female:67	Male: 23 Female:10	Male: 12 Female:6	Male:11 Female:19
Prior Experience in Surgical Procedure	Yes: 1 No: 57	Yes: 8 No: 74	Yes: 5 No:29	Yes: 14 No: 4	Yes: 6 No: 14

Table 5.4. Demographics of the participants

Before discussing the results, an overview of the statistical tests used in the research is provided in the next section.

5.4 TECHNICAL DESCRIPTION OF STATISTICAL TESTS

In this section, an introduction and technical description of the statistical tests used for the analysis of the data gathered from the experiments are provided.

5.4.1 POWER ANALYSIS

Power analysis is conducted to calculate the statistical power of various statistical tests. It provides the total sample size required for given independent variables, effect size, and alpha value for any statistical test. Two types of statistical tests were conducted in this research based on the experimental design viz. T-test and Analysis of Variance (ANOVA). The Power analysis was performed using G*Power statistical software. The results of the power analysis for the T-test and ANOVA are presented below.

- For T-test
  - For Medium Effect Size (.6)
  - For Alpha (α) = 0.05
  - Total Sample Size = 148
- For ANOVA
  - For Large Effect Size (.4)
  - For Alpha (α) = 0.05
  - Total Sample Size = 112

5.4.2 TEST FOR NORMAL DISTRIBUTION

It is important to perform tests to check whether the data is normality distributed or not before analysis. Based on the normality of the data, it is decided whether to perform parametric or non-parametric statistical tests. Normality test was performed using the Jarque-Bera test. Jarque-Bera test is a goodness of fit test which demonstrates whether the data have skewness and kurtosis matching normal distribution. The results of the tests showed that the data collected for the experiments were normally distributed. Hence, parametric tests such as T-test and ANOVA were used for data analysis for the studies in this research.

5.4.3 T-TESTS

T-tests were performed for the majority of the experiments discussed in this chapter. The T-test can be considered as a type of inferential statistic which can be used to determine whether there is a significant difference between the means of two groups. These are a few assumptions to be satisfied before the t-test can be performed.

- Data follows a continuous or ordinal scale
- Data is a random sample
- Data is normally distributed
- The variance in data is homogeneous

5.4.4 ANOVA

Analysis of Variance (ANOVA) was also performed for one of the experiments discussed in this chapter. As mentioned earlier, the t-test is performed to determine the difference between the means of two groups. However, if there are three or more groups, a t-test cannot be used. In such cases, when there are three or more groups, ANOVA is used to determine if these groups are statistically different from each other or not. Another difference between t-test and ANOVA is that t-test determines the difference in mean and ANOVA determines the difference in variance between groups. These are a few assumptions to be satisfied before the ANOVA can be performed.

- Data is independent
- Data is normally distributed
- The variance in data is homogeneous

5.5 CONCLUSION

In this chapter, an overview of the assessment studies performed at multiple medical universities was presented. The statistical analysis, findings, and observations from the results were also discussed. Further, the summary of the experiments discussed in Chapter 4 is presented again. An elaboration of the dataset collected after the experiments is provided in this chapter. Finally, the technical description of the statistical tests is also included.

CHAPTER VI

AFFORDANCE STUDIES - RESULTS

6.1 INTRODUCTION

In this section, we present the results from the affordance studies. In section 6.2, the results from the affordance studies are presented. Each of the subsections in section 6.2 follows the following structure viz. (i) aim of the experiment, (ii) descriptive summary, (iii) statistical analysis, and (iv) finding. In section 6.3, a discussion on the results and findings from section 6.2 is presented.

6.2 AFFORDANCE STUDIES

A total of six experiments were conducted as part of the affordance-related studies. In this section, the results and detailed analysis of the results of each of the six experiments are presented.

6.2.1 STATIC VISUAL AFFORDANCE – EFFECT OF POSITION

A. **Aim**

A total of eighty participants interacted with the simulator to understand the effect of static position on the affordance of the scene. A comprehension assessment was conducted in which questions were asked based on the functional relationships of objects in the scene. The design of the experiment is shown below:

- Dependent Variable : Observer's **Comprehension** of the Scene
- Independent Variable : **Position** of observer (pre-specified position, observer chosen)
- Fixed Variable : Time

B. Descriptive Summary

The eighty participants were divided into two groups. The first group interacted with the environment following the pre-specified location and the second group chose their own location to interact with the environment. The participants interacted with two scenes for the experiment as shown in Table 6.1.

	Pre-Specified	**User-Specified**
Scene 1	Subject 1-40	Subject 41-80
Scene 2	Subject 41- 80	Subject 1 - 40

Table 6.1. Participants categorization for Static Visual Affordance Experiment – Effect of Position

The result of the experiment is shown in Figure 6.1. The mean comprehension score of the group who chose their location is slightly higher than the other group.

C. Statistical Analysis

A t-test was performed to test the statistical significance of the result. The result of the t-test showed that there was no significant difference between the pre-specified group (M = 57.6, SD = 11.2) and the user-specified group (M = 59.8, SD = 11.23), t (158) = 1.97, p =0.1.

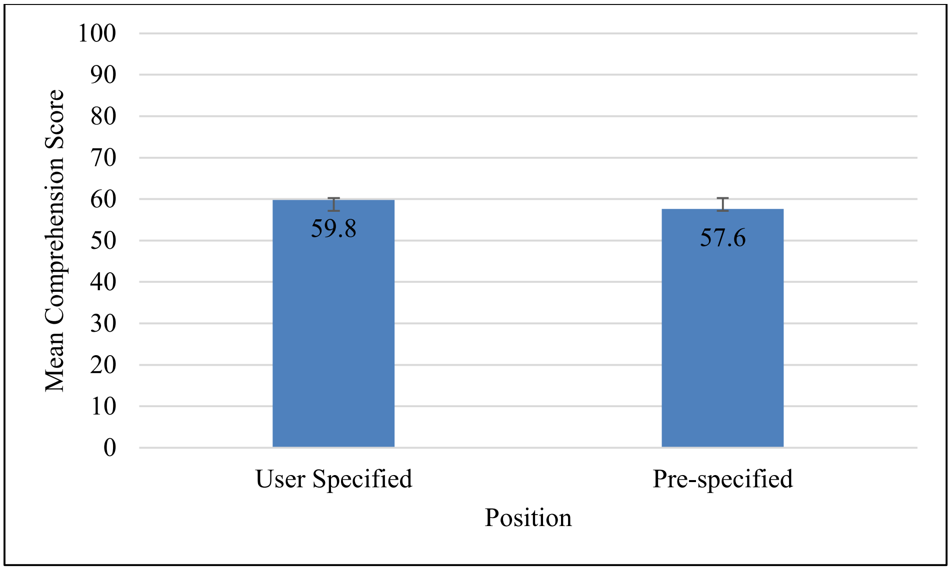


Figure 6.1. Result of Static Visual Affordance Experiment – Effect of Position

D. Finding

Although there was no difference between the user-specified and pre-specified groups, an interesting observation was made for the user-specified group in the experiment. More than 70% of the participants in the user-specified group preferred a particular position to interact with the environment. To further understand the impact, a more complicated static visual affordance study focusing on the visual density of the scene was performed.

6.2.2 STATIC VISUAL AFFORDANCE – EFFECT OF VISUAL DENSITY

A. Aim

A total of eighty participants interacted with the simulator to understand the effect of static position and visual density on the affordance of the scene. A comprehension assessment was conducted in which questions were asked based on the functional relationships of objects in the scene. The design of the experiment is shown below.

- Dependent Variable : Observer's **Comprehension** of the Scene
- Independent Variable : **Position** of observer (position 1, position 2), Visual Density of Scene (High VD, Low VD)

- Fixed Variable : Time

B. **Descriptive Summary**

The eighty participants were divided into two groups that interacted with the environments from two positions as shown in Figures 6.2 and 6.3. The participants interacted with two scenes; the first scene was an LVD scene (Figure 6.2) and the second scene was an HVD scene (Figure 6.3).

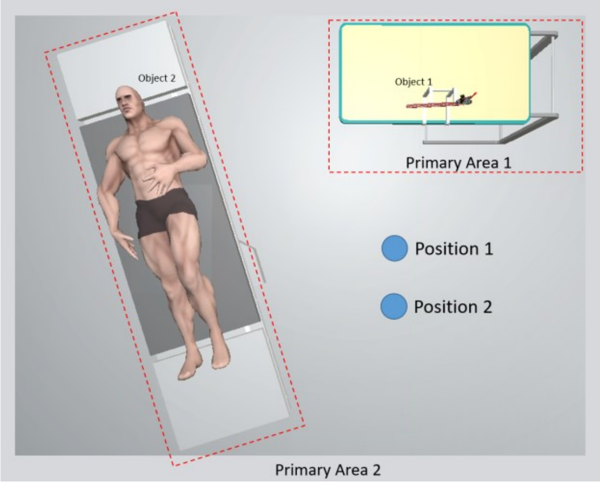


Figure 6.2. Low Visual Density Scene for the Static Visual Affordance Experiment – Effect of Visual Density

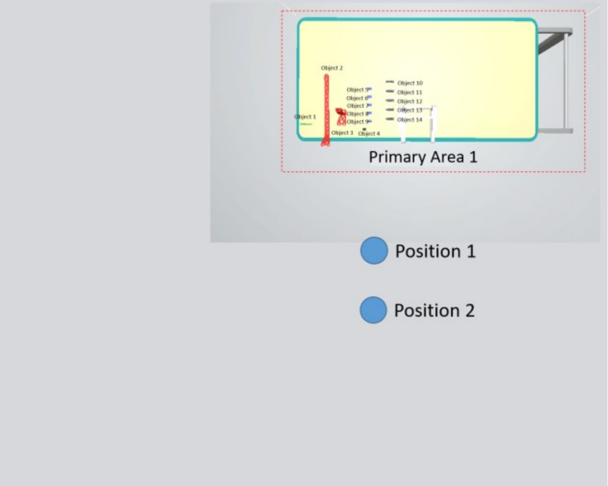


Figure 6.3. High Visual Density Scene for the Static Visual Affordance Experiment – Effect of Visual Density

	P1	**P2**
HVD	Subject 1-40	Subject 41-80
LVD	Subject 41- 80	Subject 1 - 40

Table 6.2. Participants categorization for Static Visual Affordance Experiment – Effect of Visual Density

The results of the experiment are shown in Figure 6.4. As seen in the figure, for the High VD environment, the group interacting from P1 (close to the surgical tables) received a higher score and for the Low VD environment, the group interacting from P2 (further away from the surgical tables) received a higher score in the comprehension assessment.

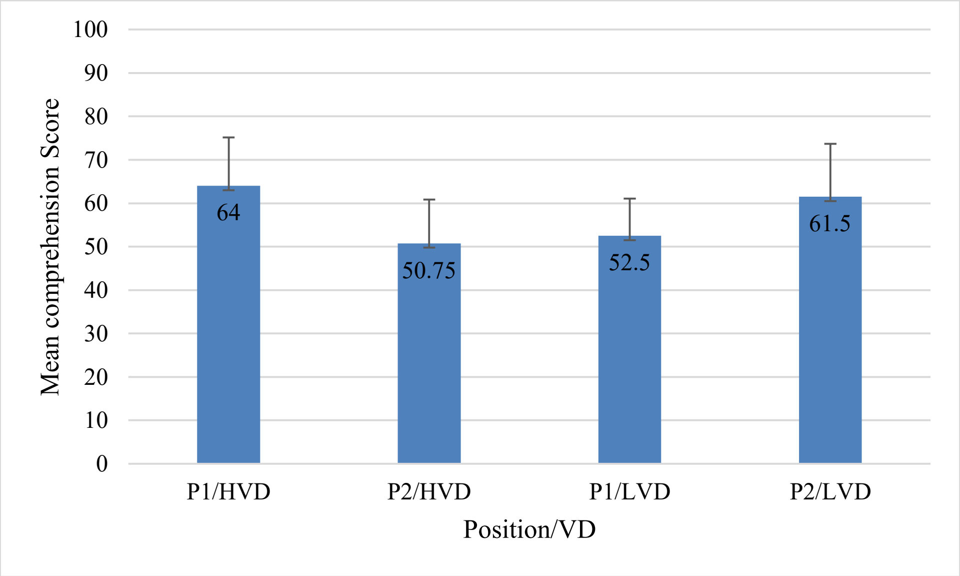


Figure 6.4. Result of Static Visual Affordance Experiment – Effect of VD

C. **Statistical Analysis**

Two T-tests were performed to test if there was a significant difference in the means of the two groups (for high and low VD environments). The result of the t-test conducted for the High VD scene shows that the score of the group interacting from P1 position (M = 64, SD = 11.1) is significantly higher than the group interacting from P2 position (M = 50.75, SD = 10), t (38) =

5.57, p =0.001. The result of the t-test conducted for Low VD scene shows that the score of the group interacting from P2 position (M = 61.5, SD = 12.1) is significantly higher from the group interacting from P1 position (M = 52.5, SD = 8.58), t (38) = 3.82, p =0.0015.

D. **Finding**

The results of the experiment showcase that visual density and position affect the affordance of the scene. The users are able to observe and comprehend the relationships between objects of interest in a high visual density environment from a closer location. However, the users comprehend the low visual density environment from a location further from the primary region. There is an indirectly proportional relationship between the density of the environment and the distance of users from the primary region. The next set of experiments focuses on understanding the effect of the dynamic path on the affordance of the environment.

6.2.3 DYNAMIC AFFORDANCE – EFFECT OF PATH

A. **Aim**

A total of eighty medical personnel participated in this study to understand the effect of path on the affordance of an environment. The experimental design of the study is presented below.

- Dependent Variable : Observer's **Comprehension** of the Scene
- Independent Variable : **Path** of observer (Center, Peripheral)
- Fixed Variable : Time

B. **Descriptive Summary**

The eighty participants were divided into two groups. The first group interacted with the environment 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 6.5).

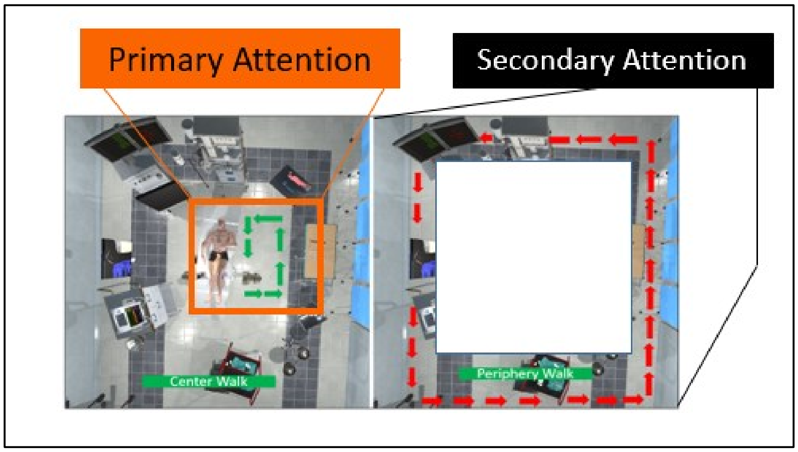


Figure 6.5. Primary attention and Secondary Attention Area of the scene

	Subjects
Center Path	Subject 1-40
Peripheral Path	Subject 40-80

Table 6.3. Participants categorization for Dynamic Affordance Experiment – Effect of Path

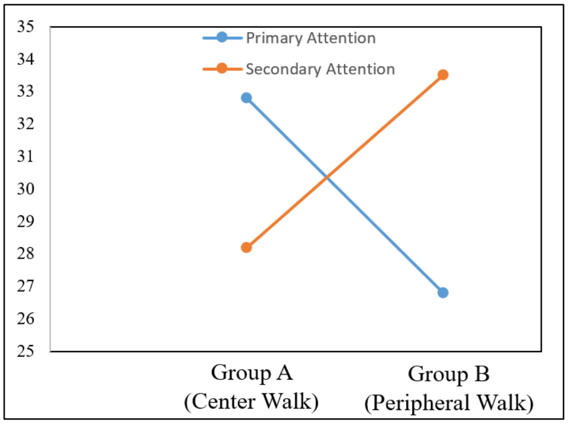


Figure 6.6. Result of Dynamic Affordance Experiment – Effect of Path

The results of the experiment are shown in Figure 6.6. 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.

C. Statistical Analysis

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.

D. Finding

The results showcase that there is no specific path that the users can follow to comprehend the scene exhaustively. Each path helps the users to understand a certain section of the environment. The users understand the relationships between OOIs in the primary attention area better while following a central path. If the users need a comprehensive understanding of the secondary area, the peripheral path is the optimal path to follow. In the next set of environments, the users were given the freedom to choose their path during the interactions with the environments.

6.2.4 DYNAMIC AFFORDANCE – EFFECT OF GUIDANCE

A. Aim

A total of eighty participants interacted with the environment to understand the impact of guidance provided on affordance. The participants were given the freedom to choose their own path during such interactions. The experimental design for the study follows.

- Dependent Variable : Observer’s **Comprehension** of the Scene
- Independent Variable : **Guidance** provided (Avatar, Hand Model)
- Fixed Variable : Time

B. Descriptive Summary

The participants interacted with two environments for this experiment. In the first environment, the participants performed the task of assembling the condylar plate and in the second environment, they performed the task of lag technique. For both the environments, half the participants observed an avatar performing the task and the other half observed a hand model performing the tasks.

	Avatar	Hand Model
Task 1	Subject 1-40	Subject 41-80
Task 2	Subject 41- 80	Subject 1 - 40

Table 6.4. Participants categorization for Dynamic Affordance Experiment – Effect of Guidance

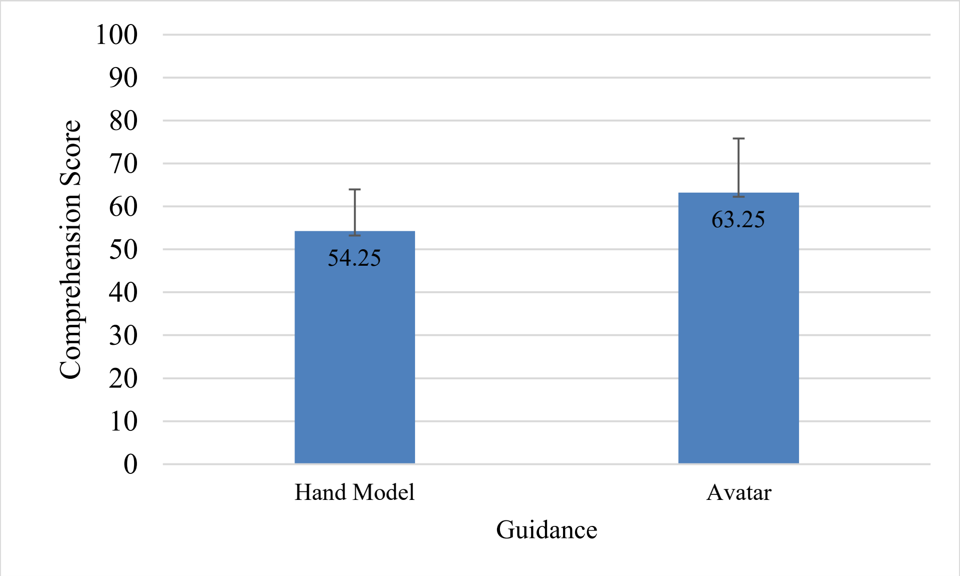


Figure 6.7. Result of Dynamic Affordance Experiment – Effect of Guidance

C. Statistical Analysis

The result of the experiment is shown in Figure 6.7. The t-test result revealed the group interacting with the Avatar model (M = 63.2, SD = 12.5) received significantly higher comprehension score compared to the group interacting with the hand model (M = 54.2, SD = 9.7), t (158) = 5.07, p = 0.001.

D. **Finding**

The results showcase that avatar models help the users learn more effectively. The higher realism when learning from Avatar might be a reason for the result. Further, we analyzed the results of the group which interacted with the hand model separately to understand the effect of the random path taken by the users. The results of the study showed that a majority (65%) of participants typically moved around objects in a perimeter path to gain a better understanding of the target scene. Subsequently, they moved closer to obtain a better grasp of the final details of a target task. The participants walked around to the back of the scene only in situations where one object (equipment, part, hand model) was blocking the field of view which prevented them from understanding a target task being observed.

6.2.5 DYNAMIC AFFORDANCE – EFFECT OF CUES

A. **Aim**

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 experimental design for the study follows.

- Dependent Variable : Observer's **Comprehension** of the Scene
- Independent Variable : **Cues** provided (Voice, Text)
- Fixed Variable : Time

B. **Descriptive Summary**

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.

	Voice	Text
Task 1	Subject 1-40	Subject 41-80
Task 2	Subject 41- 80	Subject 1 - 40

Table 6.5. Participants categorization for Dynamic Affordance Experiment – Effect of Cues

C. Statistical Analysis

The results of the experiment show that the group interacting with voice-based cues scored higher compared to the group interacting with the 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.

D. Finding

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.

6.2.6 TACTILE AFFORDANCE

A. Aim

The aim of this experiment was to understand the impact of the sense of touch on the affordance of a scene. The experimental design for this study follows.

- Dependent Variable : Observer’s **Comprehension** of the Scene
- Independent Variable : Type of **touch response** (Haptic device, Vive based controller)

- Fixed Variable : Time

B. Descriptive Summary

A total of eighty participants interacted with two environments (plate insertion and dynamic plate compression) in this study.

	Haptic Device	Vive Controller
Task 1	Subject 1-40	Subject 41-80
Task 2	Subject 41- 80	Subject 1 - 40

Table 6.6. Participants categorization for Tactile Affordance Experiment

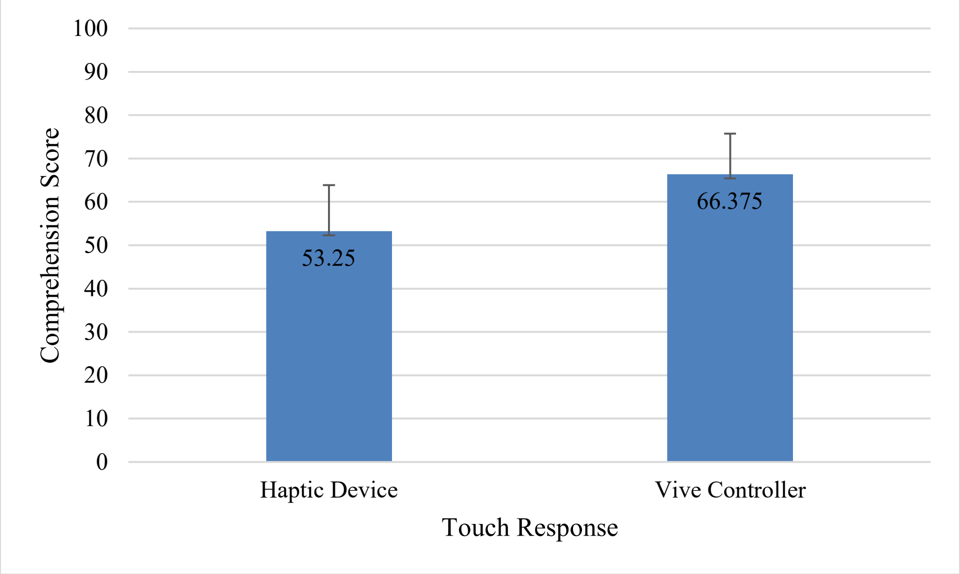


Figure 6.8. Result of Tactile Affordance Experiment

C. Statistical Analysis

The result of the tactile affordance experiment is shown in Figure 6.8. According to the result of the t-test, the group interacting with the Vive controller (M = 66.3, SD = 9.38) received significantly higher score compared to the group interacting with the haptic device (M = 53.25, SD = 10.5), t (158) = 8.3, p = 0.001.

D. **Finding**

Although the haptic device provided the sense of touch, there is a limitation in motion during the interaction. The Vive controller, on the other hand, provides the users with unrestricted motion. This could be the main reason behind the result. However, when asked about their preference during the force-based tasks such as drilling, more than 80% of the participants preferred the haptic device over the Vive controller. The haptic-based interface through vibrations and force feedback provides a more realistic replication of the actual drilling procedure.

The statistical results which favor the vive controller do not completely justify the role of haptic interfaces for surgical training. The substantial preference for the haptic interfaces shown by the users is a confirmation of the need for haptic interfaces. Haptic interfaces can be very useful in surgical procedures where force-feedback becomes necessary such as drilling, fracture reduction, among others. Currently, haptic devices are widely used in laparoscopic and orthopedic simulators [2, 27, 45-47] despite of the restricted motion associated with the haptic interfaces. Haptic interfaces have the potential to co-exist in an integrated manner with other XR interfaces.

6.3 DISCUSSION

The affordance-related studies demonstrated that there doesn't exist any particular position or path that provides the maximum affordance to the user. The best position or path depends on the nature of the target scene. For some scenarios, the users preferred to walk in the center of the room, observing the target scene as they are rotating about their axis. For other scenarios, the users comprehended more while walking on the periphery of the target scene. Further, experiments were also conducted to investigate the impact of the user-chosen path during the interactions with training environments with varying levels of complexity, different types of guidance models (Avatar, hand models), and cues (voice, texts). One of the examples was is shown in which the users choose his/her path during interaction with the training environments. During the interactions, the majority typically moved around objects in a perimeter, path to gain a better understanding of the target scene and then moved closer to obtain a better grasp of the final details of a target task The users walked around to the back of the scene only in situations where one object (surgical equipment, avatar, monitors) was blocking the field of view which prevented them from understanding a target task being observed.

6.4 CONCLUSION

In this chapter, an overview of the assessment activities for the affordance studies was presented. In the later part of the chapter, findings, and discussions related to the results were elaborated.

CHAPTER VII

COGNITIVE LOAD STUDIES - RESULTS

7.1 INTRODUCTION

In this section, we present the results from the cognitive load studies. In section 7.2, the results from each of the cognitive load studies are presented (7.2.1, 7.2.2, and 7.2.3). Each of the subsections in section 7.2 follows the following structure viz. (i) aim of the experiment, (ii) descriptive summary, (iii) statistical analysis, and (iv) finding. In section 7.3, a discussion on the results and findings from section 7.2 is presented.

7.2 COGNITIVE LOAD STUDIES

A total of three experiments were conducted to understand the impact of additional cognitive load on the users during the interactions with the training environments. In this section, the results and analysis of the results of the experiments are presented.

7.2.1 EFFECT OF STRESS INDUCERS

A. **Aim**

The aim of the experiment is to understand the impact of stress inducers on the knowledge and skills acquisition of the users. A total of eighty participants interacted with the Lag Technique training environment in this experiment. The experimental design of the experiment is shown below.

- Dependent Variable : Skills and Knowledge Acquisition
- Independent Variable : Stress inducers (No inducers, inducers)

B. Descriptive Summary

The participants were divided into two groups, the first group interacted with the environment without any stress inducers, and the second group interacted with the environment with stress inducers. Two stress inducers were introduced in the scene, the first inducer involved patiently shaking and making noises with an increase in heart rate, and the second inducer involved blood hemorrhage during the interactions with the patient.

No Inducers	Stress Inducers
Subject 1-40	Subject 41-80

Table 7.1. Participants categorization for Cognitive Load experiment - Effect of Stress Inducers

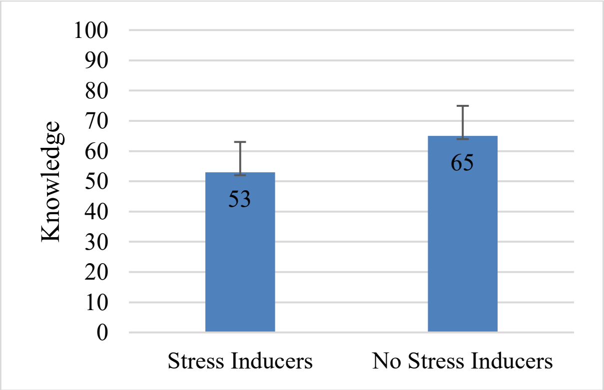


Figure 7.1. Result of Cognitive Load experiment - Effect of Stress Inducers (Knowledge Assessment)

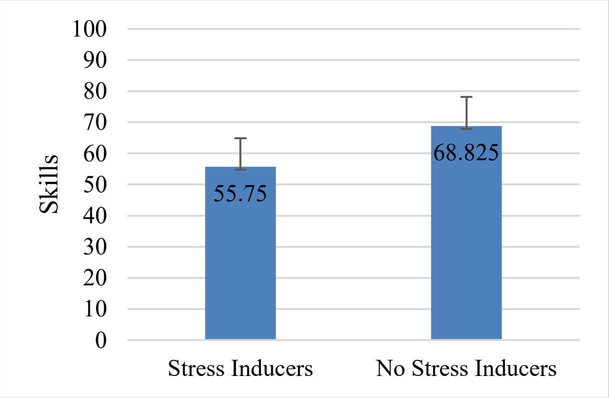


Figure 7.2. Result of Cognitive Load experiment - Effect of Stress Inducers (Skills Assessment)

C. Statistical Analysis

As seen in Figures 7.1 and 7.2, the participants who were introduced to stress inducers received lower scores in both skills and knowledge assessment. Two T-tests were also performed to test if there was a significant difference in the means of the two groups (with stress inducers and without stress inducers). The results from the t-test for the skills assessment show a significant difference in mean in the group interacting with stress inducers (M = 55.75, SD = 9.08) and the group interacting without stress inducers (M = 68.82, SD = 9.30), t (78) = 6.35, p =0.001. The results from the t-test for the knowledge assessment also show a significant difference in mean in the group interacting with the stress inducers (M = 53, SD = 10) and the group interacting without the stress inducers (M = 65, SD = 10.04), t (78) = 5.35, p = 0.001. As seen in Figures 7.3 and 7.4, both the heart rate and pupil dilation increase are higher for the group who were introduced to stress inducers.

D. Finding

The results also ensure the fact that participants indeed were cognitively loaded during the interactions with the environment with stress inducers. The additional cognitive load led to a decrease in scores for both skills and knowledge assessment. This underscores the need for the inclusion of stress inducers based on real-life surgical scenarios early on during the XR-based training.

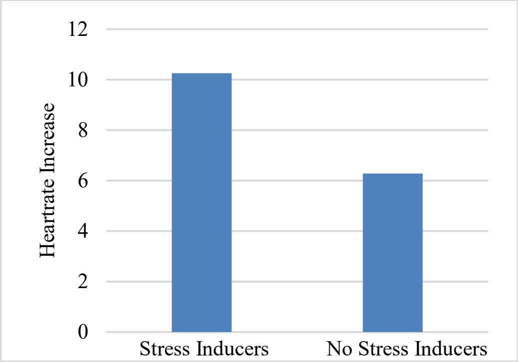


Figure 7.3. Heart rate increase during the interaction with the environment

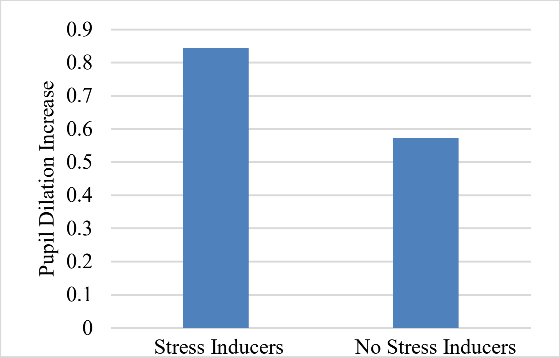


Figure 7.4. Pupil dilation increase during the interaction with the environment

A further analysis was performed to understand the impact of stress inducers based on the experience level of the participants. The group which interacted with the environment with stress inducers were divided into two groups based on their experience level. The first group was composed of nursing students and the second group was composed of practicing nurses. The results of the analysis are shown in Figures 7.5 and Figure 7.6. It can be observed from the figures that the nurses gained higher scores in both knowledge and skills assessment compared to the nursing students.

The practicing nurses have had experienced such stress inducers during real-life scenarios, hence they seem to be less impacted due to the additional load. On the other hand, the nursing students do not get the same opportunity to face such stress inducers which were impactful during training. The XR training environments targeted towards students should include such stress-based scenarios as part of the training objective.

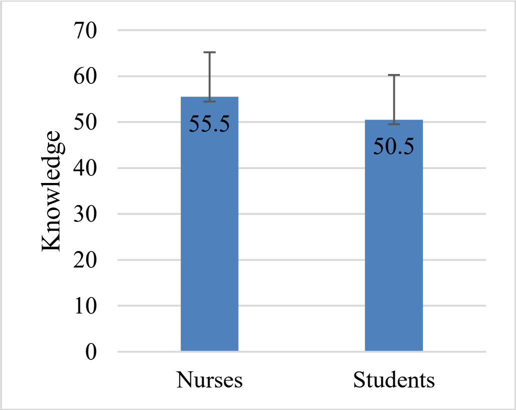


Figure 7.5. The scores of practicing nurses and nursing students in the knowledge assessment

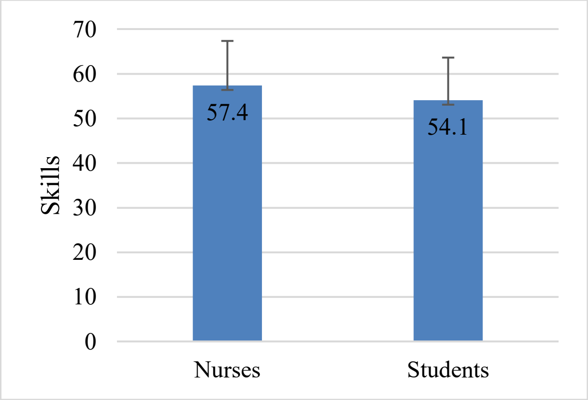


Figure 7.6. The scores of practicing nurses and nursing students in the skills assessment

7.2.2 EFFECT OF DISTRACTIONS

A. **Aim**

The aim of this experiment is to understand the effect of distractions on the knowledge and skill acquisition of the users. A total of 120 participants interacting with the training environments for this experiment.. The experimental design of the experiment follows.

- Dependent Variable : Skills and Knowledge Acquisition
- Independent Variable : Distractions (No distractions, audio, visual, audio-visual)

B. Descriptive Summary

The participants were divided into four groups. The first group interacted with the environment without any distractions. The second group was exposed to audio distractions (sirens, ambulance sounds) and the third group was exposed to visual distractions (nurse walk in abruptly, tables falling). The fourth group interacted with both audio and visual distractions

	Subjects
No Distractions	30
Audio	30
Visual	30
Audio-visual	30

Table 7.2. Participants categorization for Cognitive Load experiment - Effect of Distractions

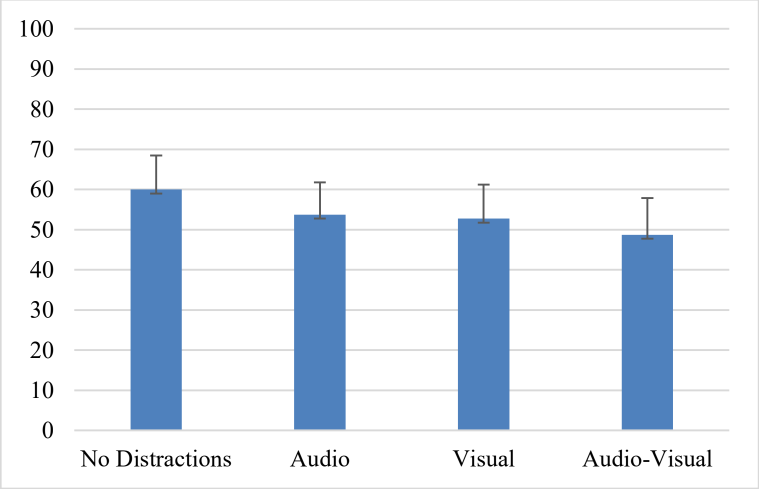


Figure 7.7. Result of Cognitive Load experiment - Effect of Distractions

Pairwise Comparisons		(Honest Significant Difference) $HSD_{.05} = 4.9580$ $HSD_{.01} = 6.0413$	(Studentized Range Distribution) $Q_{.05} = 3.6726$ $Q_{.01} = 4.4750$
No Distraction: Audio	$M_1 = 60.00$ $M_2 = 53.75$	6.25	Q = 4.63 (p = .00709)
No Distraction: Visual	$M_1 = 60.00$ $M_3 = 52.75$	7.25	Q = 5.37 (p = .00119)
No Distraction: Audio-Visual	$M_1 = 60.00$ $M_4 = 48.75$	11.25	Q = 8.33 (p = .00000)
Audio: Visual	$M_2 = 53.75$ $M_3 = 52.75$	1	Q = 0.74 (p = .95324)
Audio: Audio-Visual	$M_2 = 53.75$ $M_4 = 48.75$	5	Q = 3.70 (p = .04725)
Visual: Audio-Visual	$M_3 = 52.75$ $M_4 = 48.75$	4	Q = 2.96 (p = .15922)

Table 7.3. Result of ANOVA for the Cognitive Load experiment - Effect of Distractions

C. **Statistical Analysis**

The result of the experiment is shown in Figure 7.7. It can be seen that the users who were exposed to audio-visual distractions received the lowest score. ANOVA was performed to further understand the impact of such distractions. The results of ANOVA are shown in Table 7.3. The results indicate that there is a significant difference between group interacting without distractions and group interacting with distractions. It can also be observed that there is no difference between the group exposed to audio distractions and the group exposed to visual distractions. Further, it was illustrated that there was a difference between the group exposed to audio distractions and the group exposed to visual distractions. However, no difference was observed between the group exposed to visual distractions and the group exposed to audio-visual distractions.

D. **Finding**

The audio-visual distractions impact the users the most followed by the visual distractions. The visual distractions, especially, tend to divert the focus of the users from the virtual surgical procedure being performed leading to lower scores in the skills and knowledge assessment.

7.2.3 EFFECT OF REPETITION

A. **Aim**

The aim of the experiment was to understand the effect of repetition on the skills acquisition of the users. A total of eighty participants interacted with the plate insertion training environment. The experimental design is shown below.

- Dependent Variable : Skills Acquisition
- Independent Variable : Repetition (Low (2), High (5))

B. **Descriptive Summary**

The participants were divided into two groups; the first group repeated the training twice before performing the challenge and the second group repeated the training five times before performing the challenge.

Low (2)	**High (5)**
Subject 1-40	Subject 41-80

Table 7.4. Participants categorization for Cognitive Load experiment - Effect of Repetition

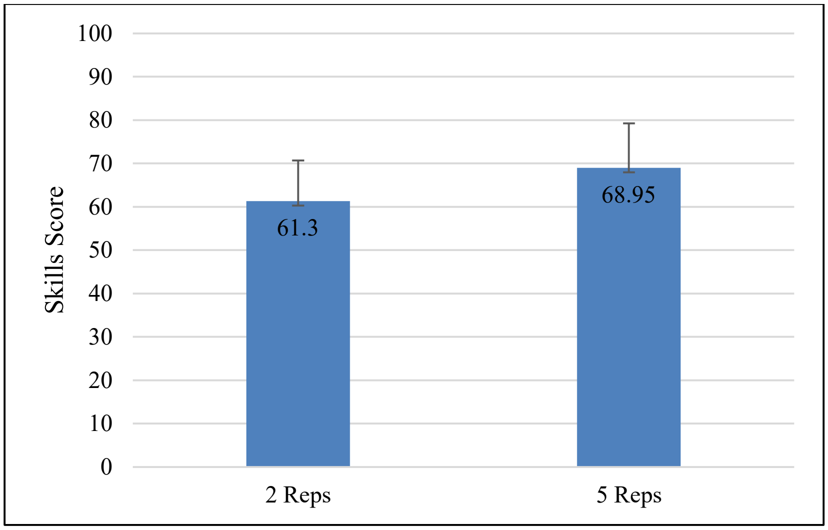


Figure 7.8. Result of Cognitive Load experiment - Effect of Repetition

The result of the experiment is shown in Figure 7.8. As seen in the figure, the group performing five repetitions received a higher score compared to the group performing only two repetitions.

C. Statistical Analysis

In order to further understand the impact, a t-test was performed. The results of the t-test showcase that that the high repetition group (M = 68.9, SD = 10.26) scored significantly higher compared to the low repetition group (M = 61.3, SD = 9.35), t (78) = 3.48p = 0.04. A further analysis was performed to understand the effect of repetition on participants' heart rate and pupil dilation increase. The results are shown in Figures 7.9 and 7.10. It can be observed from the figure that both heart rate and pupil dilation starts to become steady after the third repetition.

D. Finding

The results show that the cognitive load slowly decreases on the users due to multiple repetitions. The results underscore that repetition help the users to learn tasks more effectively. As the users get acclimatized to the training environments after multiple repetitions, the cognitive load on the users flattens. The result of this study underscores and supports the main value proposition of

XR-based training environments is the ability to repeat in a safe environment without wasting physical resources.

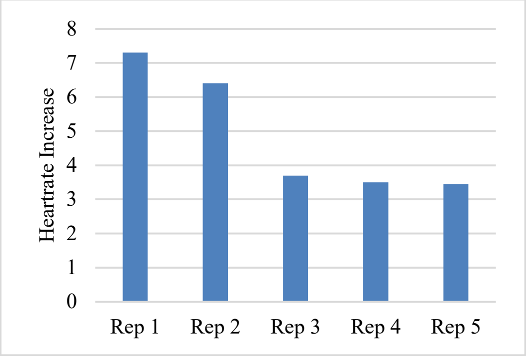


Figure 7.9. Heart rate increase after each repetition

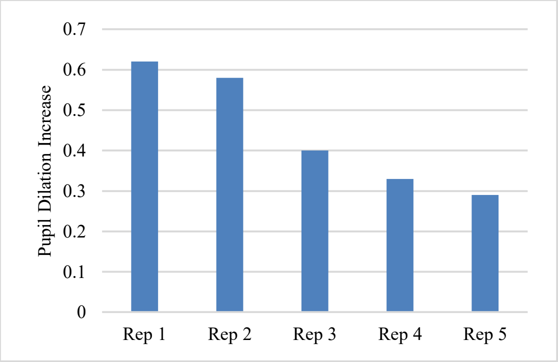


Figure 7.10. Pupil dilation increase after each repetition

7.3 DISCUSSION

In this research, we had focused on including multiple types of cognitive load which impact the user during their interactions with the training environments. Some loads were intrinsic to the surgical procedure (related to the patient) and other loads were external loads (such as outside distractions and disturbances). Further, we also investigated how repeating a training procedure impacted the load imposed on the users. The research experiments conducted have led to the conclusion that the intrinsic load (stress inducers) does impact the user's knowledge and skills acquisition negatively. However, the cognitive load experienced by a user depends upon (a) the complexity of the 3D training environment and (b) the seniority and healthcare work experience of the users. (E.g. Nursing student and nurses). In terms of external disturbances, the audio-visual distractions impacted the learning of the users negatively the most. Further, it was also observed that virtual repetition of the training procedure helped in lowering the cognitive load on the users which in turn improved their skills acquisition.

7.4 CONCLUSION

In this chapter, an overview of the assessment activities for the cognitive load studies was presented. In the later part of the chapter, findings, and discussions related to the results were elaborated.

CHAPTER VIII

COMPARISON STUDIES - RESULTS

8.1 INTRODUCTION

In this section, we present the results from the comparison studies. In section 8.1, the results from each of the comparison studies are presented (8.2.1 and 8.2.2). Each of the subsections in section 8.2 follows the following structure viz. (i) aim of the experiment, (ii) descriptive summary, (iii) statistical analysis, and (iv) finding. In section 8.3, a discussion on the results and findings from section 8.2 is presented.

8.2 COMPARISON STUDIES

A total of two experiments were conducted for the comparison studies. In this section, the results and detailed analysis of the results of the two experiments are presented.

8.2.1 COMPARISON STUDY – MR AND VR

A. **Aim**

In this experiment, the focus was on understanding the usefulness of MR and VR in different scenarios with varying levels of complexity. A total of eighty participants interacted with MR and VR environments with two levels of complexity. The low complexity task was plate assembly and the high complexity task was dynamic plate compression. The design of the experiment is shown below. The participants were divided into groups of nursing students and practicing nurses. The participants performed low complexity task first; subsequently, they performed high complexity task.

- Dependent Variable : Skills and Knowledge Acquisition
- Independent Variable : Platform (VR, MR)

B. Descriptive Summary

	VR	MR
Task 1	Subject 1-40 (20 Nursing students, 20 Nurses)	Subject 41-80 (20 Nursing students, 20 Nurses)
Task 2	Subject 41- 80 (20 Nursing students, 20 Nurses)	Subject 1 – 40 (20 Nursing students, 20 Nurses)

Table 8.1. Participants categorization for Comparison Study – MR and VR

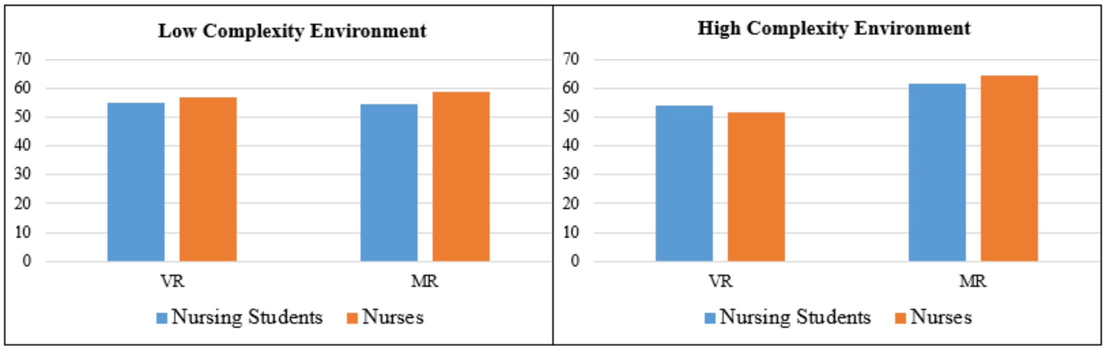


Figure 8.1. Result of Comparison Study –VR and MR Low complexity environment (left) and VR and MR High complexity environment (right)

The results of the experiment for comparison of MR and VR environments are shown in Figure 8.1. It can be seen from the figure that the difference in score depended on the complexity of the environment for both the nursing students and practicing nurses group. It was also observed that for low complexity scenarios for both VR and MR and high complexity scenarios, the practicing nurses scored higher than the nursing students which was expected. However, for the high complexity VR scenario, the nursing students scored higher than the practicing nurses which was unexpected. This could be due to the motivation and/or fatigue-related variables. Another reason could be that the practicing nurses must have applied themselves more in the MR scenarios than in VR scenarios. This could also be due to the fact that nurses had to go back to work and were less focused on the VR task.

The results also show that the users in both nursing students and practicing nurses groups scored higher in the high complexity task than in the low complexity task. This result could be due to the ordering of the tasks. As the users first interacted with the low complexity task, they did not have enough practice and experience interacting with the XR environments leading to lower scores. However, they would have gained some practice and experience before interacting with the high complexity task (during their interaction with the low complexity task) which led to higher scores for the high complexity task.

C. **Statistical Analysis**

Two t-tests were performed for both nursing students and practicing nurses groups to further analyze the results.

Nursing students group: For the low complexity environments, no significant difference was observed in scores between the group interacting with VR (M = 55, SD = 8.06) and the group interacting with MR environment (M = 54.5, SD = 9.2), t (38) = 0.18, p = 0.42. However, for the high complexity environments, a significant difference was observed in scores between the group interacting with VR (M = 54, SD = 8.6) and the group interacting with MR environment (M = 61.5, SD = 5.72), t (38) = 3.24, p = 0.001.

Practicing nurses group: For the low complexity environments, no significant difference was observed in scores between the group interacting with VR (M = 57, SD = 9.53) and the group interacting with MR environment (M = 59, SD = 12.6), t (38) = 0.56, p = 0.55. However, for the high complexity environments, a significant difference was observed in scores between the group interacting with VR (M = 51.5, SD = 8.5) and the group interacting with MR environment (M = 64.5, SD = 9.2), t (38) = 3.24, p = 0.0003.

D. **Finding**

The research experiments concluded have led to the conclusion that both VR and MR technologies are capable of providing surgical training to the users. The complexity of the environment and the experience level of the users are the major factors influencing the results of the study. The study focusing on experience level also provides evidence that VR platform can serve as the first level of training and MR platform can serve as the second level of training. After getting experience on the VR platform, the users can become more proficient when learning on the second level of training (MR platform). Further, the modified NASA TLX test scores showed that the nurses preferred to interact with the MR platform compared to the VR platform. In daily life, the nurses constantly interact with physical equipment. They also need to practice on the physical mannequin (Figure 8.2) at a certain interval of time to sharpen their skills. The nurses' preference for the MR platform could be due to their ease of interaction with physical equipment and mannequin.

Figure 8.2. A view of the physical mannequin for practice of nurses

8.2.2 COMPARISON STUDY – ONE MAIN TASK AND MULTIPLE SUB TASKS

A. **Aim**

The aim of the experiment is to understand the effect of performing one main task vs multiple small tasks leading to the main task. A total of eighty participants interacted with the plate insertion environment. The design of experiment is shown below.

- Dependent Variable : Skills and Knowledge Acquisition
- Independent Variable : Task (Main Task, Sub Tasks)

B. **Descriptive Summary**

The participants were divided into two groups; the first group performed only the plate insertion task whereas the second group performed two sub-tasks such as hand jitteriness task and task involving avoiding nerves and arteries before performing the plate insertion task.

Main Task	**Sub Tasks**
Subject 1-40	Subject 41-80

Table 8.2. Participants categorization for Comparison Study – One Main Task and Multiple Sub Tasks

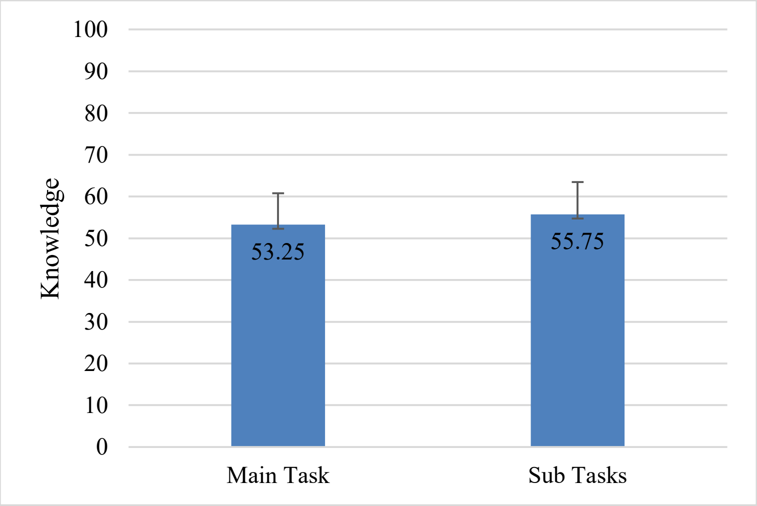


Figure 8.3. Result of Knowledge Assessment – One Main Task and Multiple Sub Tasks

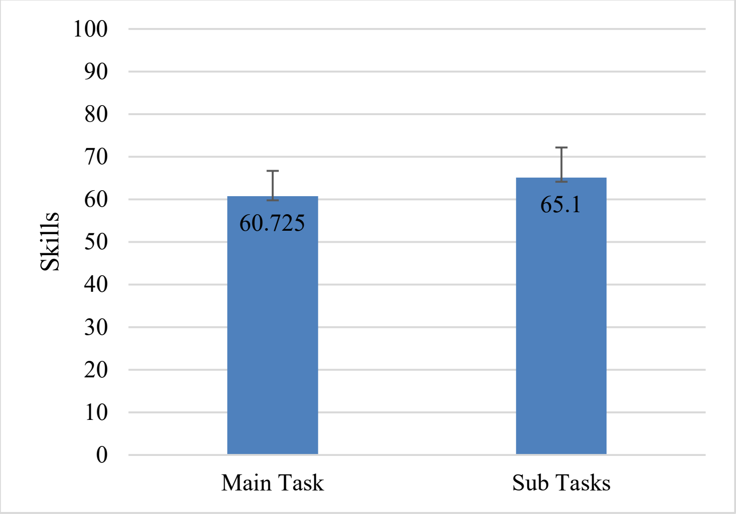


Figure 8.4. Result of Skills Assessment – One Main Task and Multiple Sub Tasks

The results of the study are shown in Figures 8.3 and 8.4. As seen in figure 8.3, there isn't much difference in the knowledge assessment scores for the two groups. However, the group performing sub-tasks scored higher than the group performing the main task in the skills assessment (Figure 8.4).

C. Statistical Analysis

In order to further understand the results, two t-tests were performed. The result of the t-test for the knowledge assessment shows no difference between the main task group (M = 53.25, SD = 7.54) and sub-task group (M = 55.75, SD = 7.70), t (78) = 1.46, p = 0.07. However, the result of the t-test for the skills assessment shows significant difference between the main task group (M = 60.72, SD = 5.97) and sub-task group (M = 65.1, SD = 7.05), t (78) = 2.99, p = 0.02.

D. Finding

The result of this study showcase that skill acquisition is highly impacted by dividing complex tasks into multiple small tasks. The users learn skills-based tasks effectively when interacting with multiple sub-tasks. If the training objective in the XR-based environments is complex in nature, it should be subdivided into smaller sub-objectives for effective training.

8.2.3 NETWORKING STUDIES

Performance of GENI Network

During the learning interactions on the network-based simulator, the performance of the GENI-based network with respect to latency was also studied. Internet Control Message Protocol (ICMP) ping was used to measure the network latency.

Access	Average Latency (ms)		
	User 1	User 2	User 3
2 Users	48.35	48.2	N/A
3 Users	48.7	48.5	48.9

Table 8.3. Latency data for network based Haptic Simulator

Table 8.3 shows the latency data when the network-based simulator was used simultaneously by 2 and 3 users from different locations (the latency was measured between the user's computer and the server). The latency data was collected for a 2-hour period. The results (Figure 8.5) from the test show that the average latency is stable at around 48 milliseconds (which is an acceptable measure).

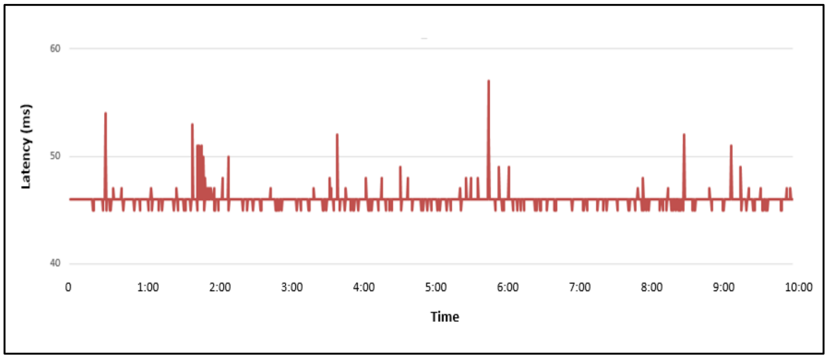


Figure 8.5. Latency graph for network-based interactions for two users

8.3 DISCUSSION

In this research, we have focused on understanding the usefulness of MR and VR in different scenarios with varying levels of complexity. The research experiments concluded have led to the conclusion that both VR and MR technologies are capable of providing surgical training to the users. Participants who were trained using Mixed Reality environments demonstrated significant improvement for the complex environment. There was not much significant difference between MR and VR environments for low complexity environments. It was also observed that the experience level of the users impacts the preference of MR and VR-based environments. We performed experiments (described in section 8.2) with two levels of complexity (high and low) with nursing students and experienced nurses to support the conclusion provided above. It was also observed that users acquire better skills while interacting with sub-tasks before completing the main task. However, such interactions with the sub-tasks before the main task didn't show any significant difference in knowledge acquisition.

8.4 CONCLUSION

In this chapter, an overview of the assessment activities for the comparision studies was presented. The results related to the next generation networking approach were also presented in the chapter. In the later part of the chapter, findings, and discussions related to the results were elaborated.

CHAPTER IX

CONCLUSION

9.1 INTRODUCTION

In this chapter, an overview of the dissertation is presented in section 9.2. In section 9.3., the chapter-wise summary of the dissertation is provided. The characterization of an effective XR-based training environment based on the assessment results is presented in section 9.4. The significance of the research is discussed in section 9.5. A delineation of the future work based on this research is presented in section 9.6.

9.2 OVERVIEW OF THE DISSERTATION

This research outlined an HCI-based framework designed for the creation of XR-based training activities for orthopedic surgical training. The orthopedic surgical procedure in focus was the condylar plating surgery. Condylar plating surgery is performed to treat the fractures of femur bone by inserting a plate inside the patient's leg. The framework was designed using a participatory design approach which supported the creation of information models. The information models served as the foundation for the creation of the framework. HCI-based design criteria such as affordance, visual density, and cognitive load were taken into consideration during the design of the framework. Further, an innovative integrated assessment approach was presented. A summary of each of the dissertation chapters is provided in this chapter. Further, a discussion regarding the future research based on this dissertation is also included in this chapter.

9.3 DISSERTATION SUMMARY

9.3.1 CHAPTER 1 SUMMARY

This chapter provided a brief introduction of the research and definitions which served as the background of the research. Definitions of terms such as XR, HCI, and HCI-based design criteria, participatory design and information modeling were presented in this chapter. In addition, a problem statement and the set of objectives for the research were also formalized in the latter part of this chapter.

9.3.2 CHAPTER 2 SUMMARY

An exhaustive literature review of related work was presented in this chapter. The chapter included a review of topics such as XR-based simulators in surgery and orthopedic surgery, HCI-based design criteria such as affordance, cognitive load, visual density, participatory design approach, information modeling, and assessment approaches. A table showcasing current research being performed on various aspects of the HCI-based framework was also presented. Finally, research voids in the current literature were also elaborated in this chapter.

9.3.3 CHAPTER 3 SUMMARY

This chapter provided an overview of the overall HCI-based framework. A discussion was presented on each component of the framework such as participatory design and information modeling, HCI-based design criteria, design of XR-based training environments, and integrated assessment approach. A brief elaboration of the design of experiment developed for the assessment of the XR-based environments was also presented.

9.3.4 CHAPTER 4 SUMMARY

In chapter 4, the results and outcomes of the assessment activities were presented. The assessment activities were divided into three groups of studies viz. affordance studies, cognitive load studies, and comparison studies. A detailed description of each study including the statistical tests and analysis was presented in this chapter. A discussion related to the finding from each of the studies was also elaborated in this chapter. Finally, a discussion about the characteristics of an effective XR-based training environment was presented.

9.4 CHARACTERIZATION OF AN EFFECTIVE XR TRAINING ENVIRONMENT

Based on the results and discussion, several observations were made which can help characterize an effective XR-based training environment for surgical training. Some of the observations which can serve as design considerations follow.

- Position can be crucial during automated simulation-based training

  The position can play a critical role when the users are observing an automated simulation. The designers should consider different positions and choose the optimal viewing position for such automated simulation.

- Different paths can provide the understanding of different areas of the environment

  Different paths taken by the users can help comprehend information regarding different areas of the target scene. The designers should first have a clear understanding regarding the objective of the scene and subsequently, decide if a structured path is necessary to convey the objective of the scene to the users.

- Avatars can be useful for conveying complex surgical steps

  The use of 3D avatars to show complex surgical steps of the surgical procedure such as lag technique. The users are able to clearly focus on the nuances of the hand and body movements when an avatar is performing the surgical step.

- Tactile interface can be useful for surgical procedures where force feedback is essential

  Tactile interface such as the haptic device can be useful to understand surgical steps such as drilling and fracture reduction. The understanding of such steps can be enhanced using the tactile interface.

- Cognitive Load related scenarios should be designed based on the complexity of the scene and the users' experience level

  The cognitive load experienced by a user depends upon (a) the complexity of the 3D training environment and (b) the seniority and healthcare work experience of the users. (E.g. Nursing student and nurses). The designers should consider the complexity of the environment and the experience level of the users during the design of the training environments.

- The selection of MR and VR platforms should be considered based on criteria such as
    - Complexity of the environment
    - Experience level of the users

  Further, two levels of training environment can be created using the VR and MR platforms. The designers can consider the VR environment as the first level of training. The users can first get trained in VR-based training. Subsequently, they can become more proficient after interacting with the physical mockup in MR-based second level of training.

9.5 RESEARCH SIGNIFICANCE

In this research, the design of an HCI-based framework for the creation of XR-based environments for surgical training has been discussed. The framework was designed using a participatory design approach in which expert surgeons were involved from the beginning of the project to the validation and assessment. Expert surgeons also contributed towards the creation of information models. The creation of such models can be useful for the design and development of other complex systems as well, especially in the creation of XR-based environments in other domains such as manufacturing, education, space systems, among others.

HCI-based design criteria such as affordance, visual density, and cognitive load were utilized during the creation of XR-based environments. In this research, new measures have been proposed related to dynamic and tactile affordance; another key contribution is the study of the relationships of these existing and newly proposed attributes to each other as well as to a 3D VR scene's comprehension and understanding have been explored. This research will serve as a blueprint for other researchers who want to introduce HCI based design approach in their research. New measures such as dynamic affordance can be utilized by other researchers, especially in the area of XR, to conduct studies to create user-centered environments.

An integrated assessment approach including assessment of comprehension, knowledge, skills and cognitive load has been presented in this research. The assessment activities are designed based on Design of Experiment (DoE) methodologies. Such an assessment approach and experimental design can be utilized by other research as well to assess and validate their training environments.

9.6 FUTURE WORK

- Expansion of current work

  The scope of the work has been limited as the research was getting broader. In the future, the scope can be expanded and more studies with a larger number of participants can be performed. Some of the studies for future work are

  - Understanding the role of a secondary person in the surgery environment

    In the future, a secondary avatar (surgeon assistant) can be introduced which can serve as an assistant to the users helping in picking up tools and equipment from the table, verbally presenting the vital signs of the patients, among others. It will be interesting to observe the role of such secondary characters in surgical training.

  - Response to stress inducers

    The current XR environments include two stress inducers. The number of such inducers can be increased to showcase more of the real-life scenarios. Further, environments training the users in how to respond during such stressful scenarios can be developed.

- IoT based Framework for Remote Surgery

  The current framework can serve as a blueprint for the design of an IoT framework based on a cloud overlay network to support remote surgical procedures involving cyber-physical resources. Using the framework, multiple surgeons (from different locations) will be able to propose surgical plans using XR simulators, which will then be communicated to robots that can perform the associated surgical steps on a patient (in another location).

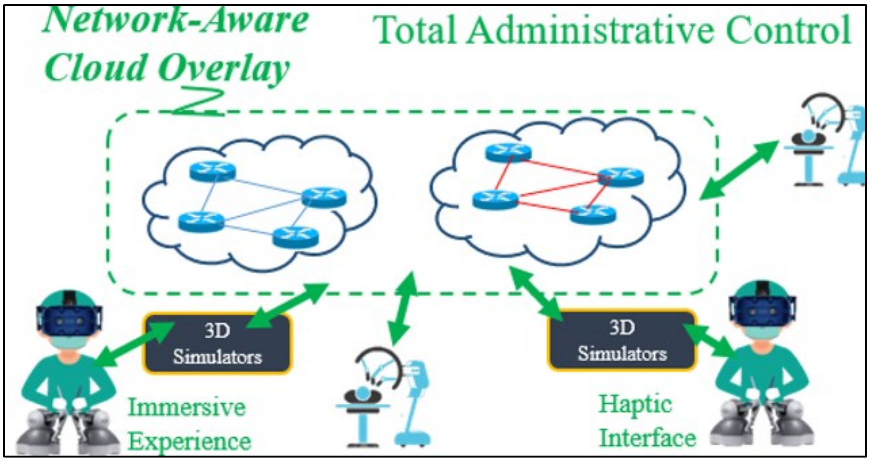


Figure 9.1. IoT based Framework for Remote Surgery

- AI-based Approaches

  Current work involves the use of an A-Star algorithm for path planning and a Genetic Algorithm for surgical planning. In the future, AI-based approaches involving machine learning can be utilized for surgical path planning involving a large number of obstacles. AI can also be used for noble surgical planning scenarios where a large number of past surgical planning data set can be used for developing optimal surgical planning scenarios.

- Use of Mixed Reality in Surgical Procedure

  In the current work, MR has been used to support surgical training involving physical mockups of the surgical equipment and bones. A continuation of current work can lead to the creation of MR based environment to support a surgeon during actual surgical procedure providing information regarding the surgical plan, the surgical path for insertion of various tools and equipment, among others.
- Implementation of the HCI framework in other domains

  The current framework is designed in a flexible manner such that, in the future, the components can be utilized for the creation of HCI based framework for the design of XR-based environments for other domains such as education, space systems, manufacturing, among others.

9.7 CONCLUSION

In this chapter, a summary of the previous chapters (chapters 1, 2, 3, and 4). The research significance of the current work was also presented. Finally, an overview of the future work that can be expanded from the current research is provided.

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APPENDICES

AFFORDANCE STUDY FOR MR ENVIRONMENT – EFFECT OF PATH

A. **Aim**

A total of forty medical personnel participated in this study to understand the effect of path on the affordance of an MR environment. The experimental design of the study is presented below.

- Dependent Variable : Observer's **Comprehension** of the Scene
- Independent Variable : **Path** of observer (Center, Peripheral)
- Fixed Variable : Time

B. **Descriptive Summary**

The forty participants were divided into two groups. The first group interacted with the environment 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.

	Subjects
Center Path	Subject 1-20
Peripheral Path	Subject 20 -40

Table A1: Participants categorization for Dynamic Affordance Experiment – Effect of Path

The results of the experiment are shown in Figure A1. 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

Figure A1. Result of Dynamic Affordance Experiment – Effect of Path

C. **Statistical Analysis**

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.

AFFORDANCE STUDY FOR MR ENVIRONMENT – EFFECT OF CUES

D. Aim

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.

- Dependent Variable : Observer’s **Comprehension** of the Scene
- Independent Variable : **Cues** provided (Voice, Text)
- Fixed Variable : Time

E. Descriptive Summary

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.

	Voice	**Text**
Task 1	Subject 1-20	Subject 21-40
Task 2	Subject 21-40	Subject 1-20

Table A2: Participants categorization for Dynamic Affordance Experiment – Effect of Cues

F. Statistical Analysis

The results of the experiment show that the group interacting with voice-based cues scored higher compared to the group interacting with the 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 ($M = 61.5$, $SD = 9.6$), scored significantly higher than the group interacting with text cues ($M = 50.5$, $SD = 9.7$) , $t(38) = 3.59$, $p = 0.05$.

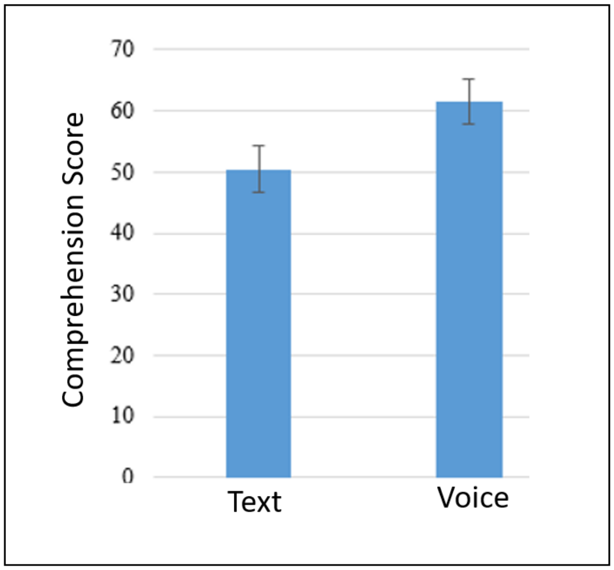


Figure A2: Results – Effect of Cues

COGNITIVE LOAD STUDY FOR MR ENVIRONMENT – EFFECT OF STRESS INDUCERS

A. Aim

The aim of the experiment is to understand the impact of stress inducers on the knowledge and skills acquisition of the users. A total of forty participants interacted with the Dynamic Plate Compression training environment in this experiment. The experimental design of the experiment is shown below.

- Dependent Variable : Skills and Knowledge Acquisition
- Independent Variable : Stress inducers (No inducers, inducers)

B. Descriptive Summary

The participants were divided into two groups, the first group interacted with the environment without any stress inducers, and the second group interacted with the environment with stress inducers. Two stress inducers were introduced in the scene, the first inducer involved patiently shaking and making noises with an increase in heart rate, and the second inducer involved blood hemorrhage during the interactions with the patient.

No Inducers	Stress Inducers
Subject 1-20	Subject 40-80

Table A3. Participants categorization for Cognitive Load experiment - Effect of Stress Inducers

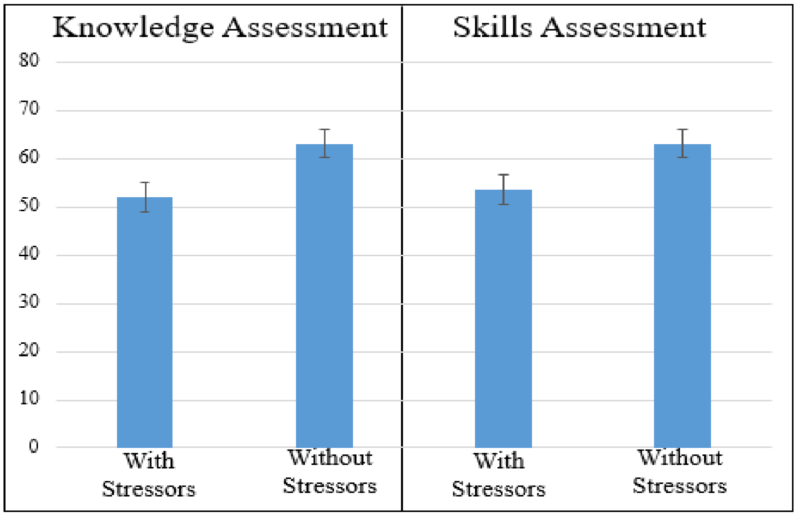


Figure A3. Result of Cognitive Load experiment - Effect of Stress Inducers (Knowledge Assessment)

(left) and (Skills Assessment) right

C. **Statistical Analysis**

As seen in Figure A3 above the participants who were introduced to stress inducers received lower scores in both skills and knowledge assessment. Two T-tests were also performed to test if there was a significant difference in the means of the two groups (with stress inducers and without stress inducers). The results from the t-test for the skills assessment show a significant difference in mean in the group interacting with stress inducers (M = 53, SD = 10.0) and the group interacting without stress inducers (M = 66, SD = 8.6), t (38) = 4.39, p =0.05. The results from the t-test for the knowledge assessment also show a significant difference in mean in the group interacting with the stress inducers (M = 55.5, SD = 9.7) and the group interacting without the stress inducers (M = 66, SD = 8.6), t (38) = 4.39, p =0.05. As seen in Figure A4 below, the heart rate is higher for the group who were introduced to stress inducers.

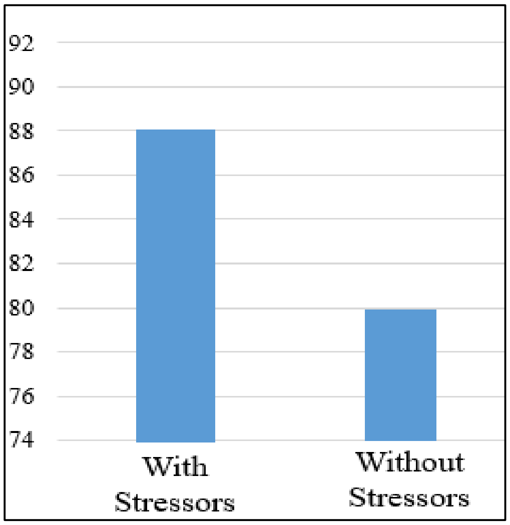


Figure A4: Heart rate of participants

NASA TLX Test Results for MR – VR comparison study

After the interactions with the MR and VR-based training environments, the eighty participants responded to a modified NASA Task Load Index (TLX) [71] survey. The modified NASA TLX survey was developed to assess the usability of an environment and the cognitive load on the users during the interaction with an environment. The survey shows the effect of the complexity of an environment on usability. Further, the survey also provides the subjective measure of cognitive load on the users during interactions with training environments with increasing levels of complexity. In the survey, the participants were asked to rate the MR and VR environments on twelve criteria which are shown in Table A3.

Criteria (Rating between 1- 10)
1. Clarity of the instructions in the AR/VR platform.
2. The degree of usefulness of the 3D avatar-based interactions.
3. The degree of usefulness of the voice-based interactions.
4. The degree of usefulness of the text-based interactions.
5. The ease of completing tasks while wearing the headset.
6. The ease of navigating through the simulation environment.
7. The overall usefulness of the AR/VR environment.
8. Effort: How hard did you have to focus in order to complete the training? (1:Low, 10:High)
9. Frustration: How frustrated were you when trying to complete the training? (1:Low, 10:High)
10. Mental Demand: How mentally demanding was the training? (1:Low, 10:High)
11. Physical Demand: How physically demanding was the training? (1:Low, 10:High)
12. Temporal Demand: How hurried or rushed were you during the training? (1:Low, 10:High)

Table A3: Criteria for the modified NASA TLX Survey

The results of the modified NASA TLX survey show that the experienced nurses preferred MR environments whereas the nursing students preferred VR environments for the interactions. The results are shown in Figures A6 and A7. As seen from Figure A6, it is clear that the nursing students rated the VR environment higher in 10 of the 12 criteria. Further, the experienced nurses rated the MR environment higher in 11 of the 12 criteria, as shown in Figure A7.

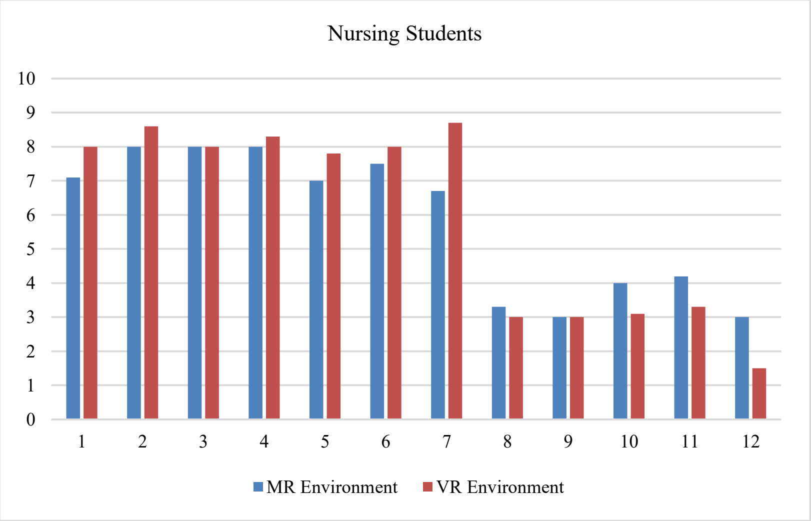


Figure A6. NASA TLX Scores of Nursing students

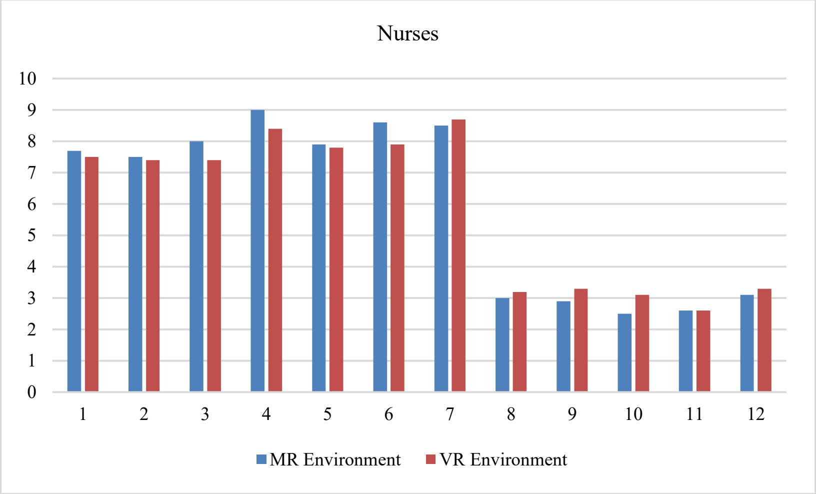


Figure A7. NASA TLX Scores of Practicing Nurses

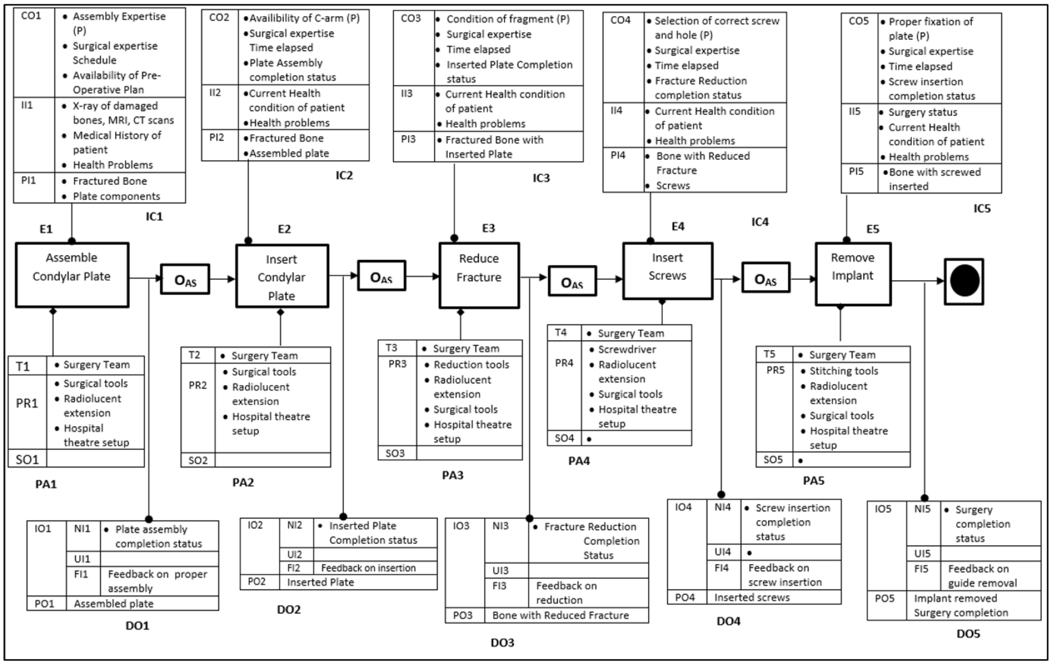


Figure A8. Conventional eEML model for Condylar Plating Procedure

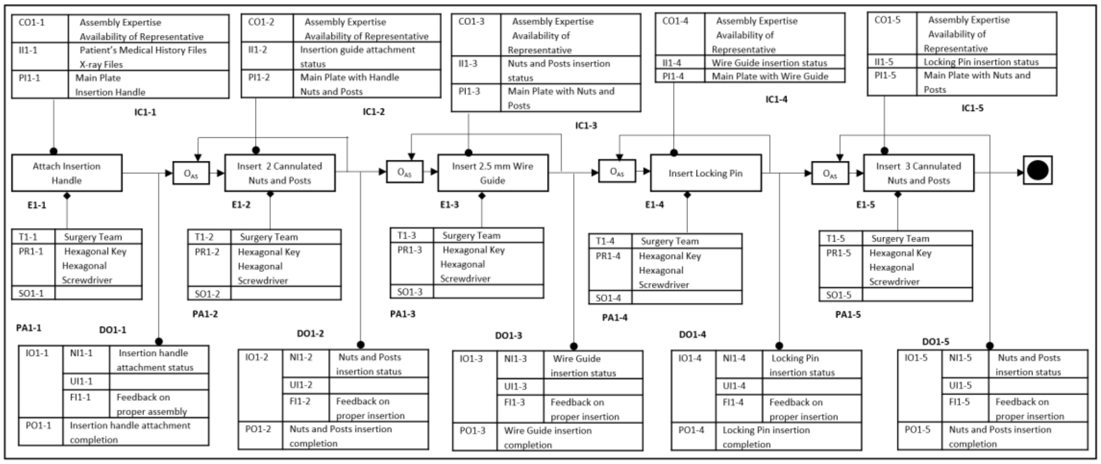


Figure A9. The decomposition model for Entity E1 (Assemble Condylar Plate)

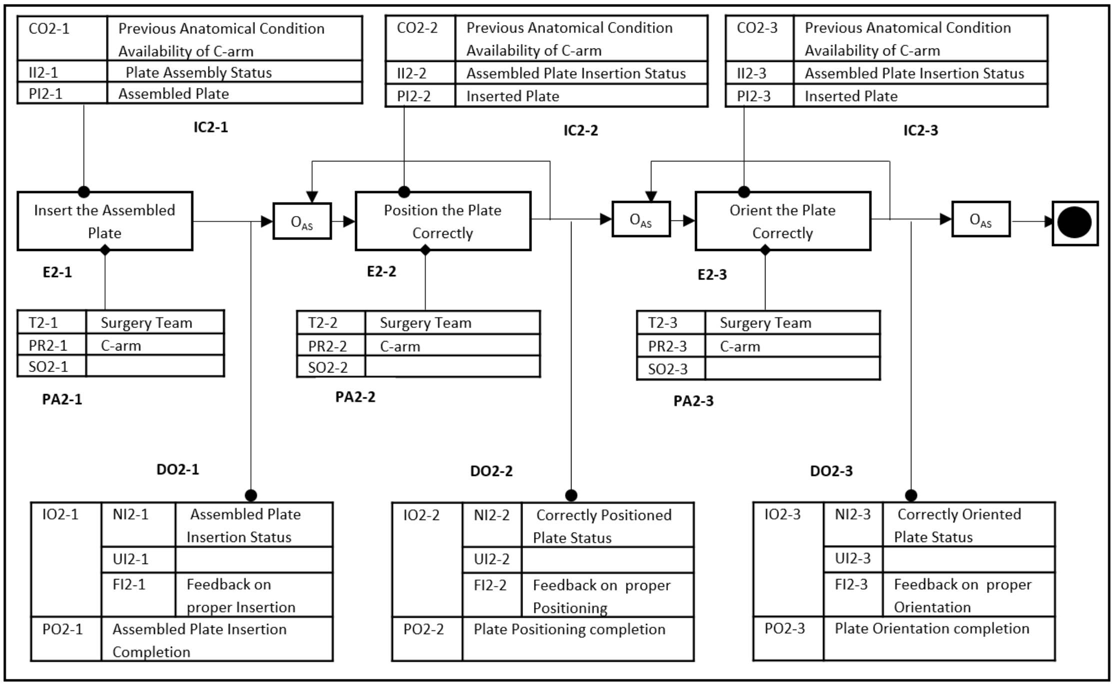


Figure A10. The decomposition model for Entity E2 (Insert Condylar Plate)

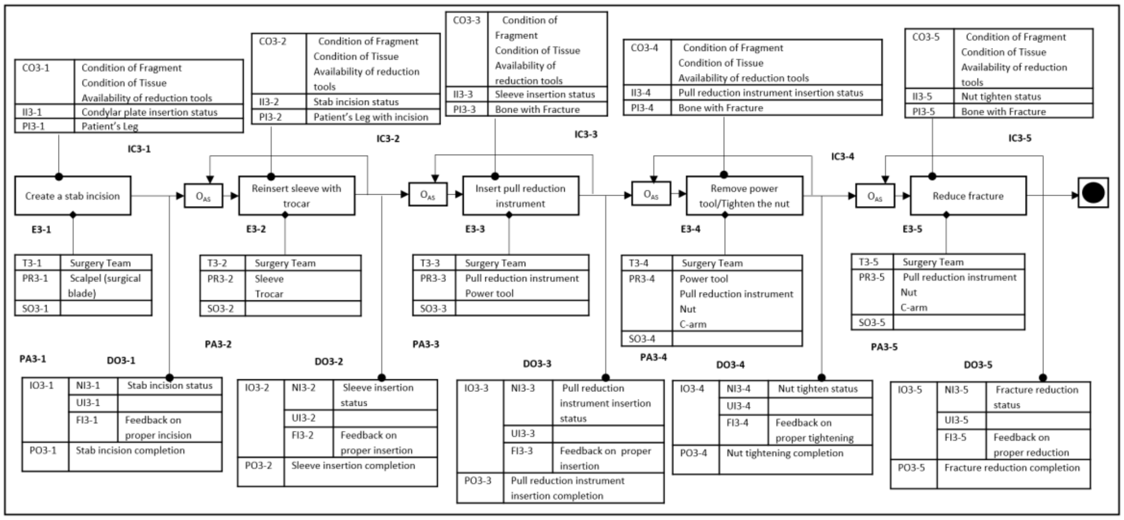


Figure A11. The decomposition model for Entity E3 (Reduce Fracture)

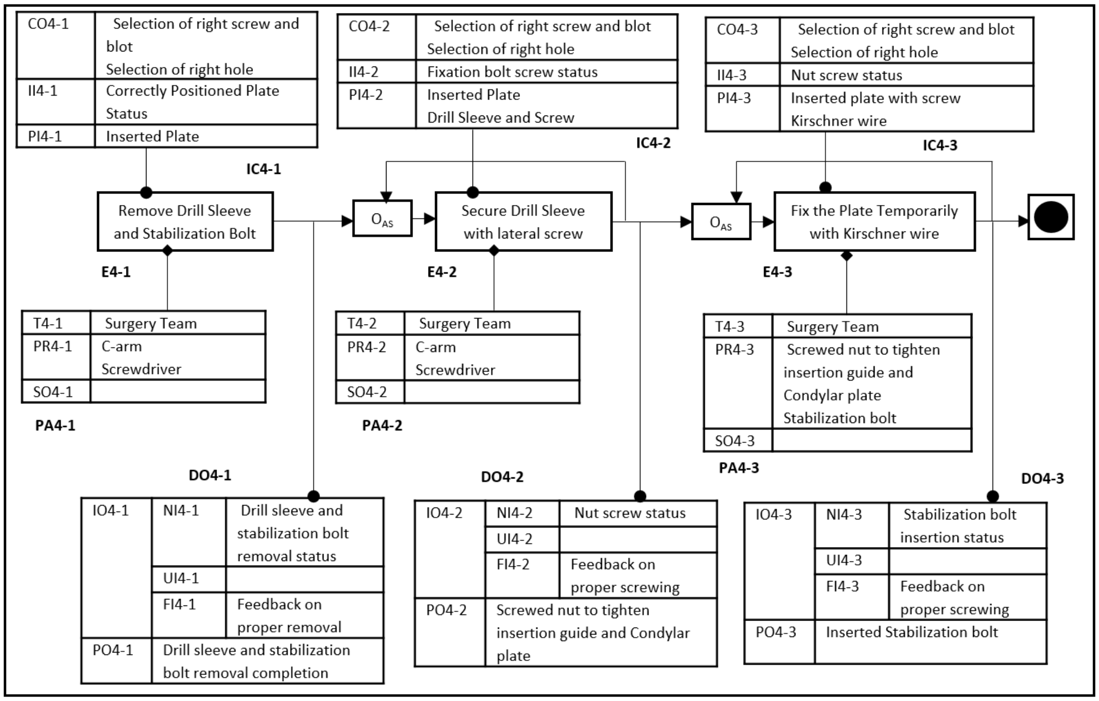


Figure A12. The decomposition model for Entity E4 (Insert Screws)

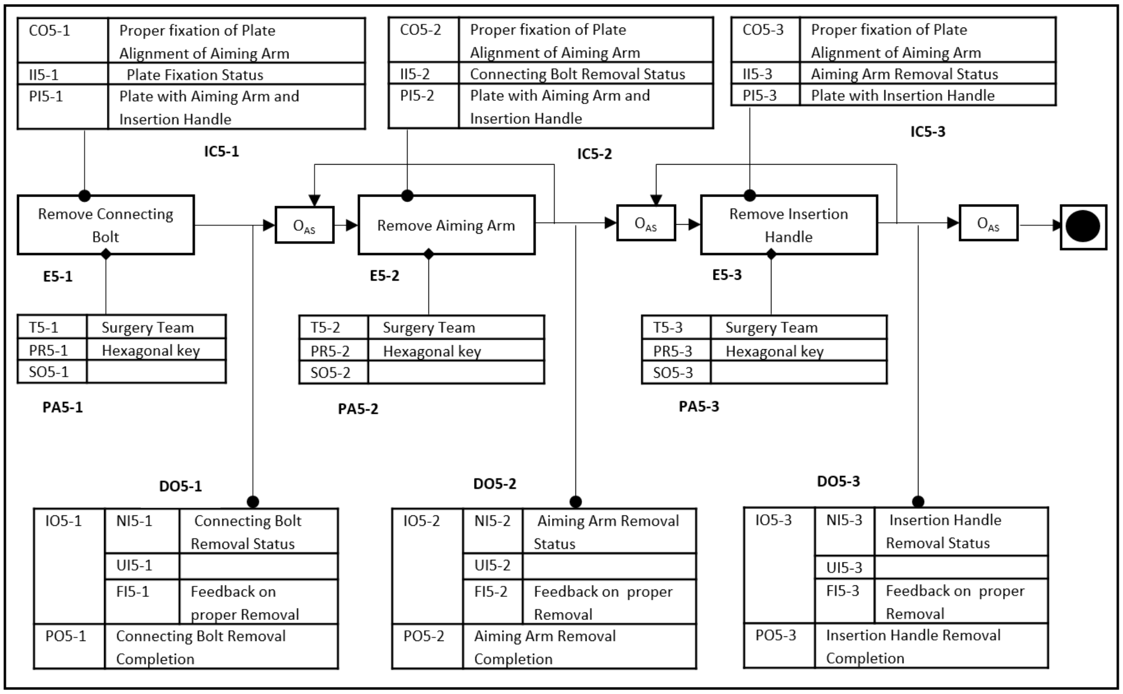
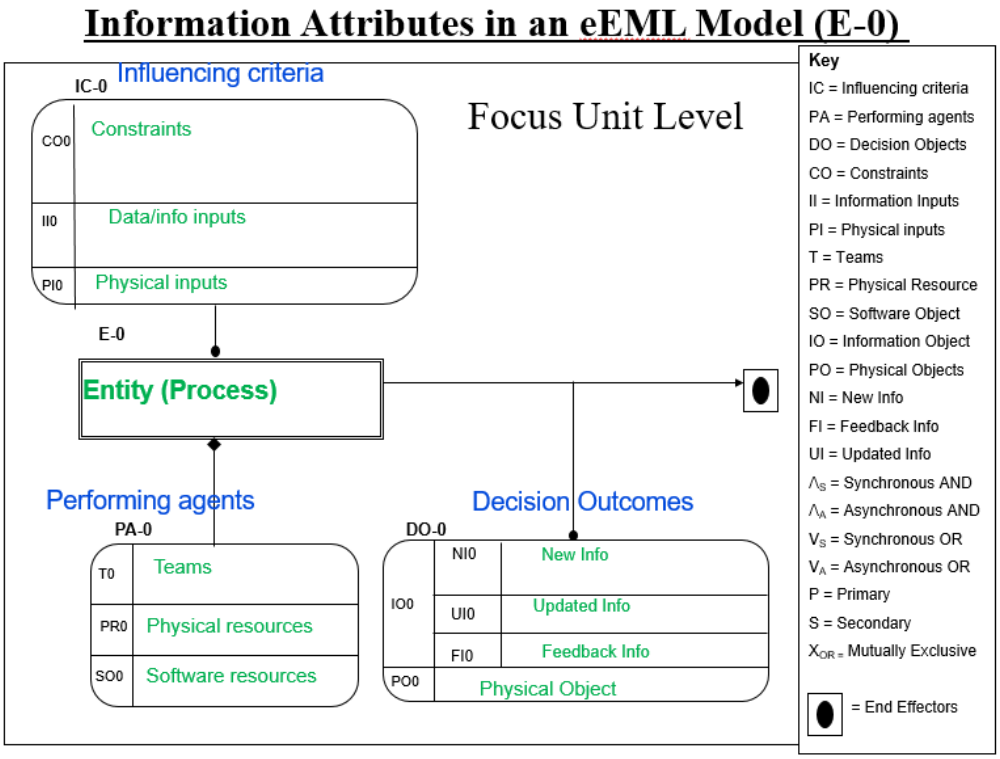


Figure A13. The decomposition model for Entity E5 (Remove Implant)



Glossary for the Top Level eEML model depicting the Condylar Plating Surgical Procedure

Assembly Expertise (P): The expertise to assemble the condylar plate correctly. It is generally performed by surgery assistant. ‘P’ means it is the primary constraint for this entity.

Surgical Expertise: The expertise in the condylar plating surgical procedure.

Availability of Pre- Operative Plan: The availability of the plan with all the information regarding the surgical procedure to be performed.

X-ray of damaged bones, MRI, CT scans: The information regarding the patient’s fracture in the form of x-rays, MRI and CT scans.

Medical History of Patient: The past medical history of patient and information regarding previous operative procedures performed

Health Problems: Information regarding health condition such as diabetics, blood pressure, etc.

Fractured Bone: The bone to be treated with the condylar plating surgical procedure

Plate Components: The components of the condylar plating surgical procedure such as insertion handle, plate, nuts, posts, locking pin, wire guide.

Surgery Team: The surgery team including Lead Surgeon, Anesthesiologist, Certified registered nurse anesthetist (CRNA), Operating room nurse or circulating nurse, Surgical tech, Residents or medical students, Physician assistant and Medical device company representative.

Surgical Tools: The tool, instrument and equipment necessary for the completion of the condylar plating surgical procedures such as k-wire, power drill, drill bit, reduction tools, screwdriver, clamps, among others.

Radiolucent Extension: A radiolucent extension table to support radiolucent scanning using the c-arm.

Hospital Theatre Setup: The hospital room for performing the condylar plating surgical procedure with the necessary machines, tables, monitors to support the surgery.

Plate Assembly Completion Status: The completion status of the plate assembly step of the condylar plating surgery.

Feedback on Proper Assembly: The feedback on the assembly procedure whether it is completed successfully or some changes are required.

Assembled Plate: The outcome of the plate assembly step of the condylar plating surgery.

Availability of C-arm (P): The availability of the c-arm which is used for radiolucent scanning during the surgical procedure.

Time elapsed: Time invested in the current surgical step of the condylar plate surgical procedure.

Current health of the patient: The health of the patient during the current surgical step being monitored by members of the surgery team.

Plate Insertion Completion Status: The completion status of the plate insertion step of the condylar plating surgery.

Feedback on Proper Insertion: The feedback on the insertion procedure whether it is completed successfully or some changes are required.

Inserted Plate: The outcome of the plate insertion step of the condylar plating surgery.

Condition of fragment (P): The condition of the fractured bone fragments before the fracture reduction is performed.

Reduction tools: The tools to perform reduction of the fracture; fracture reduction refers to repositioning of the fractured bone fragments in their correct location.

Fracture Reduction Completion Status: The completion status of the fracture reduction step of the condylar plating surgery.

Feedback on Reduction: The feedback on the reduction procedure whether it is completed successfully or some changes are required.

Bone with Reduced Fracture: The outcome of the fracture reduction step of the condylar plating surgery.

Selection of the correct screw and hole (P): Selection of the screw and hole based on the location and intensity of the fracture.

Screws: Screws used for holding the plates on the bone firmly.

Screwdriver: Screwdriver to screw the screws firmly to the plate and the bone.

Screw Insertion Completion Status: The completion status of the screw insertion step of the condylar plating surgery.

Feedback on Screw Insertion: The feedback on the screw insertion procedure whether it is completed successfully or some changes are required.

Inserted Screws: The outcome of the screw insertion step of the condylar plating surgery.

Proper Fixation of Plate: The proper fixation of the plate on the bone secured tightly with the screws.

Stitching tools: The tools required for the stitching of the cuts after the completion of the condylar plating surgery.

Surgery Completion Status: The completion status of the implant removal step which is the last step of the condylar plating surgery.

Feedback on Guide Removal: The feedback on the implant removal procedure whether it is completed successfully or some changes are required.

Implant Removed: The outcome of the implant removal step of the condylar plating surgery.

Surgery Completion: The outcome of the entire condylar plating surgery.

VITA

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