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Augmented Reality Simulation Modules for EVD Placement Training and Planning Aids

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Abstract

When a novice neurosurgeon performs a psychomotor surgical task (e.g., tool navigation into brain structures), a potential risk of damaging healthy tissues and eloquent brain structures is unavoidable when novices make multiple hits. As a result, a set of undesirable trajectories is created, and resulting in the potential for surgical complications. Thus, it is important that novices not only aim for a high-level of surgical mastery but also receive deliberate training in common neurosurgical procedures and underlying tasks.

Surgical simulators have emerged as an adequate candidate to fill the gap for effective methods to teach novices in a safe and error-free training environment. The design of neurosurgical simulators requires a comprehensive development approach. With that in mind, we demonstrate a detailed case study in which two Augmented Reality (AR) training simulation modules were designed and implemented through the adoption of Model-driven Engineering (MDE). We generated two prototypes as a proof-of-concept executables for the training and planning aids of novice neurosurgeons. The prototypes visualize three-dimensional (3D) human brain meshes and simulate a targeting task mimicking an external ventricular drain (EVD) placement task, a psycho-motor surgical task.
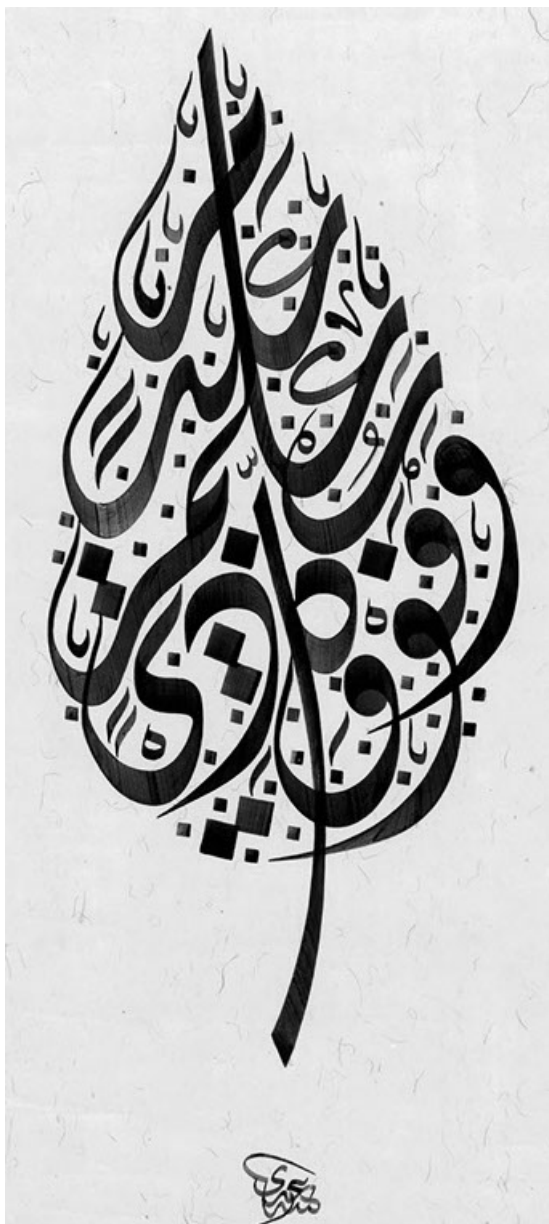
User performance evaluation is a key aspect of the surgical simulation validity. Many AR surgical simulators become obsolete; either they are not sufficient to support enough surgical scenarios, or they were validated according to subjective assessments that did not meet every need. Accordingly, we demonstrate the feasibility of the developed AR simulation modules through two user studies, objectively measuring novice users' performance based on quantitative metrics. The verification technique employed a three dimensional (3D) extension of psycho-motor-oriented methodology that is referred to as

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Paul Fitts' methodology. The data showed that novices had a learning curve and their performance as speed and accuracy trade-off was measured and reported.

Neurosurgical simulators are prone to perceptual distance underestimation. In virtual spaces, humans underestimate their egocentric distance by 80% as a result of inaccurate depth perception. Human beings are capable of perceiving 3D shapes of physical objects using perceptual motion cues. Few investigations were conducted for improving user depth perception in head-mounted display (HMD)-based AR systems with perceptual motion cues. Consequently, we report our investigation's results about whether or not head motion and perception motion cues had an influence on users' performance. The data showed that users' physical head motion and perceptual motion cues, as a combined factor, is a good indicator of better user performance.

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Dedication

"There is no chance, no destiny, no fate, that can hinder or control the firm resolve of a determined soul." By Ella Wheeler Wilcox

I dedicate this work to my parents, my wife, my family-in-law, my children, my siblings, my friends, and for every person whom provided me with kind support and encouragement.

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List of Acronyms

2D	Two-dimensional
3D	Three-dimensional
AR	Augmented Reality
CSF	Cerebrospinal Fluid
CSV	Comma Separated Values
CT	Computed Tomography
DOF	Degree Of Freedom
EP	Entry point
ER	Emergence room
EVD	External Ventricular Drain
FOV	Field Of View
GPS	Global Position System
GUI	Graphical User Interface
HCI	Human-Computer Interaction
HMDs	Head-Mounted Displays
HTA	Hierarchical Task Analysis
ICU	Intensive Care Unit
MDA	model-driven Architecture
MDE	Model-driven Engineering

MR	Mixed Reality
MRi	Magnetic Resonance Imaging
MRT	Mental Rotation Test
OR	Operating room
QR	Quick Response
PIM	Platform-independent Models
PSM	Platform-specific Models
SFM	Structure From Motion
TP	Target point
VR	Virtual Reality
UML	United Modeling Language

List of Symbols

A	Amplitude
B	Bandwidth
C	Human capacity
DE	Distance error
ID	Index of Difficulty
IP	Index of Performance
MT	Movement of Time
N	Noise power
RE	Rotational error
S	Single power source
TE	Transitional error
W	Move width

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Chapter 1

Introduction

In many clinical disciplines, preventable medical errors are considered to be a significant challenge in clinical settings (e.g., operating rooms (OR), emergency rooms (ER), or intensive care units (ICU)). In the United States of America, a study conducted by the National Practitioner Data Bank stated that at least 4000 patients were injured by preventable surgical errors between 1990 and 2010 [1]. Preventable medical errors are considered as the third leading cause of death, killing 251,000 American citizens. In Canada, the University Health Network's Annual General meeting stated that preventable medical errors cost Canadian taxpayers over $396 million annually. In 2014 alone, 30,277 Canadians died in acute care due to preventable medical errors, which makes preventable medical errors the main cause of death for Canadians—more than stroke, diabetes, Alzheimer's disease, and kidney disease combined [2]. These preventable medical errors might be a result of technical errors during complex surgeries with a hierarchy of interconnected surgical tasks. Therefore, mastery of technical surgical skills is becoming increasingly important for novice residents [1] during their training programs.

When Abraham Flexner and William Stuart Halsted proposed the concept of residency (i.e., Halstedian teaching model or apprenticeship model) [3], their training model

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1. The terms novice residents, trainees, novices, and medical students are used interchangeably throughout this thesis.

became the most used approach for surgical teaching and training. Because the surgical occupation necessitates an education that is as practical as the occupation itself [4], the apprenticeship model has been applied due to its longevity and the adoption of novel surgical techniques [5]. Although the apprenticeship model engages novice residents in real surgical scenarios and exposes them to practical tips and feedback from senior residents, the medical community has slowly been moving away from the apprenticeship model due to its disadvantages [5]. The apprenticeship model puts patients' safety at high risk of medical errors, imposes tremendous operating costs, and lacks flexibility and efficiency. Besides the apprenticeship model, conventional means (e.g., cadavers' atlases, laboratory animals, and sophisticated mannequins) have been used as supplementary materials to surgical training for the purpose of anatomical knowledge [6]. However, the conventional means also pose many educational limitations. For instance, the conventional means expose medical students to generic and static anatomical materials or different anatomical structures than human beings [7]. Also, the conventional means are unable to on mimic physiological responses that happen in clinical settings [6].

In neurosurgery, surgical training includes many supervised hours, intraoperative training on live patients, anatomical knowledge, and cognitive capabilities. Also, trainees have to master the following three stages: preoperative process (e.g., planning), operative process (e.g., intervention), and postoperative process (e.g., recovery). The preoperative stage involves maintenance of a blueprint of the neurosurgery's workflow by the application of patient-specific imaging studies. For instance, magnetic resonance imaging (MRI) or X-ray computed tomography (CT) scans are intended to represent the patient's medical situation as accurately as possible. The operative stage involves a set of deliberate

surgical interventions. The interventions include navigation or manipulation of tool tasks, for instance, placement of an external ventricular drain (EVD)'s catheter towards a designated nervous region (e.g., eloquent brain tissues) and targeting a specific fracture of the region. The postoperative stage includes a set of steps for complication management and incision closing [8].

1.1   Motivations and problem statement

Technical and non-technical skills are increasingly valuable for neurosurgeons as part of their training. Technical skills set includes manual dexterity, or specialist knowledge [9], while non-technical surgical skills set includes interpersonal and cognitive skills. Teamwork, planning, or resource management are few examples of the interpersonal skills. Situation awareness, decision making, and adaptive strategies are few examples of cognitive skills [10]. Mastery of the neurosurgery domain depends on the mixture of both skills set. However, some surgical procedures or tasks might need more emphasis on some skill set more than the others.

Although senior neurosurgeons could proctor a few early ventriculostomy[2] training sessions, novice trainees are expected to become proficient very early in their residency programs in such surgery, and they need to cope with expected high volume of operating with their own judgment for new or different neurosurgical cases [11]. Thus, it is improbable that the trainees will benefit from having an access to the same standard of

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2. Ventriculostomy is a procedure used as a surgical intervention to reduce fluid pressure in acute neurosurgical situations within lateral ventricular, a brain structure that belongs to the ventricular system.

training. This situation results in a steep learning curve in many parts of the procedure in terms of the whole operation or its interconnected psychomotor tasks, such as the EVD placement task [6].

Trainees suffer from an overwhelming cognitive load while performing EVD placement tasks within risky and interesting nervous regions, which is a source of inaccurate intervention planning [12]. Trainees need to mentally synthesize a two-dimensional (2D) version of medical imaging datasets in order to maintain a three-dimensional (3D) view of the inner nervous structure (i.e. 2D-to-3D transformation). Figure 1.1 depicts a typical trainee's behavior before committing an intervention. The process of receiving a large amount of information from multiple 2D screens at the same time might lead to position and orientation disparity between a working space (i.e., the patient's organ) and the resident's perception of the working space. This disparity could lead to inaccurate hand-eye coordination for the residents, a contributing factor for ill-posed surgical decisions. This disparity a known issue in 2D user interfaces during studying or consuming two or more imaging datasets [13]. The 3D view is a standard as a guidance base for their current surgical intervention.

Visualization technologies (i.e., Virtual Reality (VR) or Augmented Reality (AR)) are proven to be extremely useful throughout a variety of medical fields, creating novel and efficient approaches to surgical training [14][6][15]. AR has been utilized in clinical settings to project augmented or registered computer-generated models upon a particular organ with a specific patient's information [14]. The trainees, for guidance purposes, are able to visualize much-synthesized information from multiple datasets into the same display and thus gain the best of many modalities in the OR with lower cognitive efforts
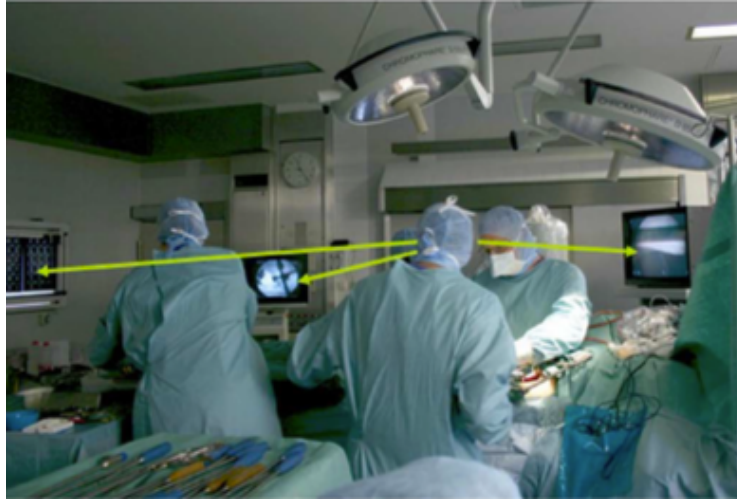
Fig. 1.1: Residents divided their attention between multiple visualization modalities to maintain a mental view and make a decision about the current surgical step [13].

[13]. Access to such training and features would empower trainees to cope with the challenge of anatomical clarity and to shorten their learning curve regarding applying novel surgical techniques [16].

There is a growing consensus amongst developers VR\AR-based simulation tools to expose trainees to risk-free training with higher percentages of gaining necessary skills. Simulation tools not only provide a capability to train novices and test novel surgical techniques but also allow senior surgeons and residency programs directors to simultaneously assess the trainees' performance and identify possible factors to improve it [15].

Although AR technology has the potential to improve the efficiency and effectiveness of current healthcare education, there are huge software gaps between the current development of AR simulation tools and clinical requirements. For example, AR simulation tools consume high person-hours costs and require thorough validation. Typical neurosurgical simulation tools use sophisticated equipment and require technical setup and expertise to prepare and operate. In addition, a variety of AR-related technical

requirements are necessary including diverse technological platforms for deployment and wider user landscapes. Moreover, the influence of human factors, for instance, cognitive ergonomics[3], plays a critical role when designing neurosurgical simulation tools [12]. Using the same AR technology for EVD placement training and planning aids with the depth perception enhancement remain a largely unexplored area that is ripe for study.

1.2 Research objectives

In this thesis, we focused on the development of an AR simulation module for an EVD placement task (i.e., psycho-motor targeting task) for training and planning aids for novice residents. Our research project had three research aims. The first aim of our study was a description of our approach to accomplish the development of AR simulation modules based on model-driven engineering (MDE)[4]. The outcome of the MDE technique produced two software executables: 1) a stationary AR module, and 2) a portable AR module. Our hypothesis was that the MDE technique is a suitable approach for the development of AR simulation tools with the flexibility to cope with technological issues in terms of patient-specific design requirements, 3D surface rendering, and the fragmentation of multiple computing platforms.

The second aim of our research was to test the feasibility of the developed AR simulation modules. Through two user studies, the verification was intended to detect

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3. Cognitive ergonomics is a field concern about mental processes and their interactions among humans and other elements of a system.

4. Although other software development processes, for instance, agile process, could be used to design and implement AR simulation modules, the current software specifications necessitate the rapid modifications of system input (i.e., neurosurgical scenarios) and fast production of prototypes. Thus, MDA is the best candidate.

quantitative differences in performance between novices with different knowledge backgrounds. The user studies were being conducted through several experimental trials in which participants conducted a variety of targeting tasks into virtual 3D ellipsoids and brain structure meshes. Statistically, discriminating evidence indicates that the AR module objectively measures the users' performance between different settings as it is claimed to assess. This data establishes the evidence to strongly advocate for the use of the AR simulation modules as a valuable assessment tool for EVD placement tasks training. Our hypothesis was that whenever users practice the EVD placement tasks with different trials, consistent feedback, and cognitive efforts, users' accuracy to perform the same tasks will improve over time.

The third aim of our research was to investigate whether or not the use of head motion and perceptional motion cues have any influence on users' depth estimation while performing EVD insertion tasks through the application of the AR simulation modules. The investigation was being conducted through several experimental trials of novices and seniors during targeting virtual 3D brain structures with, and without, the use of head motion. The experimental trials were intended to detect quantitative differences in users' performance and spatial reasoning. Statistically discriminating evidence indicates whether users' accuracy is affected as a result of improved depth estimation, due to enhanced depth perception. Our hypothesis was that users' head motion is positively correlated with enhanced depth estimation and better performance based on the use of head motion and perceptional motion cues.

1.3   Contributions

Contributions to the AR research and medical communities expected from this research are as follows:

- Provide an empirical evidence that the MDE technique could be used for the development of psychomotor-task-oriented AR simulation modules for the neurosurgical domain and possible avenues.

- Establish a methodology for quantifying users' performance using psychomotor-task-oriented AR simulation modules for the EVD placement tasks and demonstrate the developed AR simulation module assessing the skill it intends to assess.

- Understand the effect of users' physical head motion and perceptual motion cues, as a combined factor, on users' depth perception while performing EVD placement tasks through the application of the AR simulation modules.

1.4   Thesis organization

This thesis is organized into seven chapters: Chapter 2 presents related foundation and background for the research problem, Chapter 3 provides a brief overview of state-of-the-art of augmented reality systems exposing pros and cons in the context of surgical planning for EVD placement, Chapter 4 illustrates the proposed methodology to design and develop the AR simulation module, Chapter 5 presents the feasibility of AR simulation modules to be used as a methodology for quantifying users' performance, Chapter 6 presents our investigation of the influence of head motion and perceptual motion cues on

users' depth estimation, and Chapter 7 highlights the main contributions of the thesis, lessons learned, limitations, and possible avenues for future research.

Chapter 2

Literature Review

This chapter states basic definitions and background utilized to develop the ideas in this thesis.

2.1 Augmented Reality vs. Virtual Reality

AR is a visualization technology intended to enhance users' perception of reality through overlaying computer-generated information upon physical objects [16][17]. AR facilitates users' direct interaction with the physical world while maintaining a perception of the surrounding world and underlying events. VR, another visualization technology, is intended to immerse the users in a created virtual world in which the users would gain new insights and live new experiences with configurable settings [18]. VR indulges users in synthetic settings in which users cannot recognize their surroundings [16].

Milgram et al. [19] accurately described AR and VR visions through an overall presentation of how reality and Virtuality coexist through their proposed Reality-Virtuality Continuum, as depicted in figure 2.1. Figure 2.2 depicts three different visualization modes of a real historical scene of the physical world.
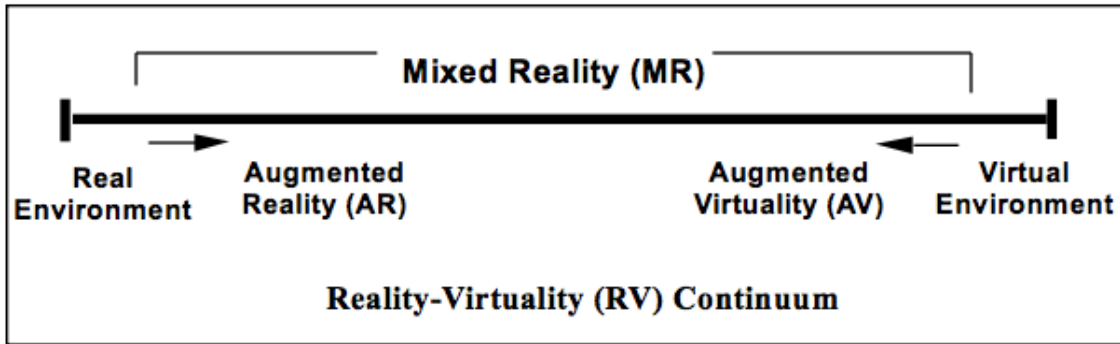
Fig. 2.1: Milgram and Kishino's continuum and the relationship between AR, VR, and real environment [19].

Fig. 2.2: (Left): the real historical scene without any modifications. (Middle) the real historical scene enhanced with AR information. (Right) the real historical scene represented in VR mode [20].

VR and AR both leverage a mixture of technologies to enable users to navigate and manipulate objects for a particular purpose in the virtual world through their own rules and coordinates system [18]. Both technologies engage users into conventional or new experiences that aren't commonly expected: a concept that possibly could revolutionize people's perception and actions in many fields. The primary goal of VR is to completely replace users' reality with a video-like experience, rather than supply their reality with augmented 3D virtual objects, as in the case of AR technology [14].

Artefact-based and geolocation-based are two modes of AR visualization. Artefact-based AR visualization mode utilizes 2D images, for instance, Quick Response (QR)

codes, barcodes or well-defined images that were scanned by a camera, as the base for the rendering process of 3D virtual information. Geolocated-based AR visualization mode utilizes location sensing and mapping references (e.g., latitude and longitude coordinates) by means of Global Position System (GPS) devices as the base for the rendering process of 3D virtual information [21].

AR technology has been used in many fields, for instance, education and medicine. Figure 2.3 shows an example of a use of an artifact-based AR app for visualization and medical purposes. When users point their AR-supported device at the desired marker, the registered medical information will be aligned with the marker, and their visual representation or feedback will emerge on the device's screen[1] [22].

Fig. 2.3: AR-based app for medical uses (source: http://www.goo.gl/yWbxhk).

Input devices, tracking devices, high-performance computer system, and modalities compose the necessary ingredients for any AR system. Digital gloves, wireless wristbands, smartphone devices' stylus or human bare-finger are a few examples of input devices. Tracking devices include any devices with sensing abilities, for instance, optical sensors, accelerometer, gyroscopic, or any sensing-based tools, that used to determine objects'

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1. Screen, display or modality will be used through the thesis interchangeably.

coordination or orientation in the physical world. The high AR demand for computing resources requires advanced computing capabilities including high processing and storage, sophisticated graphics cards, and modalities [17]).

AR modalities have been classified into three groups: head-mounted displays (HMDs), handheld displays (e.g., smartphone devices), and spatial displays (e.g., video projectors, holograms), which are depicted in Figure 2.4. HMDs involve semi-transparent mirrors attached to a helmet or goggles to illustrate real scenes and augmented 3D virtual objects over the users' sight. Handheld displays include smartphone or camera devices with which users see and consume generated or rendered 3D virtual objects upon physical objects. Spatial displays are based on projector devices to cascade graphical information directly onto physical objects in open spaces without the users' involvement to wear or carry any equipment.
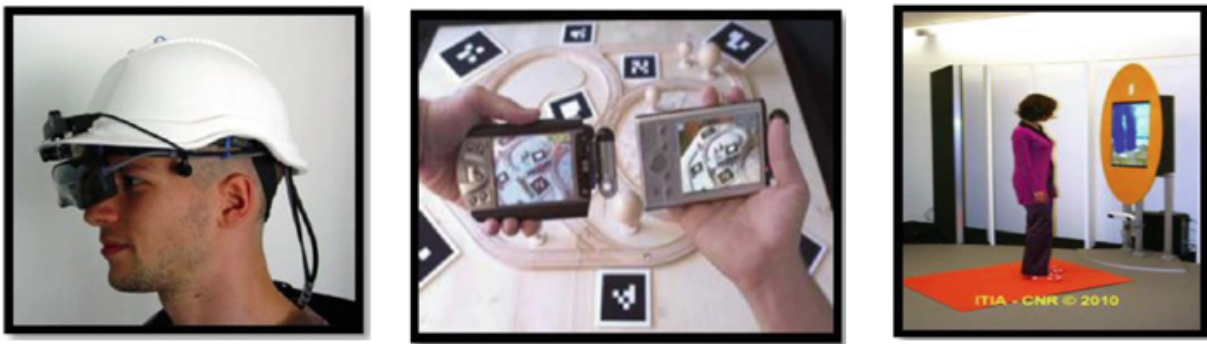
Fig. 2.4: AR displays in three different types: (left) Head-mounted display (HMD), (middle) handheld displays and (right) spatial display [17].

According to Sielhorst et al. [13], seven types of AR modalities have been used for medical training purposes. Table 2.1 presents the seven types with advantages and disadvantages for each modality [13]. HMDs are well-documented and have been utilized for their many benefits. HMDs combine real scenes and 3D virtual images in a central

setting in which users are less distracted with multiple displays; they provide researchers with possible accommodation for research prototypes and support a variety of depth perception cues. Also, because HMDs are portable and they do not show physical and virtual object occlusion problems, they allow users a 360-degree view of the surrounding physical space to visualize and interact with 3D virtual images in diverse directions. HMDs, however, have a limited field of view (FOV) and low spatial resolution, and their users might suffer from ergonomic issues due to their weight and fit [23].

Tab. 2.1: A comparison between AR modalities used in the medical domain [13].

	HMD based	Augmented optics	AR windows	Augmented monitors	Augmented endoscopes	Tomographic reflection	Projection on the patient
Improved hand eye coordination	x	x	x			x	x
Extra value from image fusion	x	x	x	x	x	x	x
Implicit 3D interaction	x	x	x				
Stereoscopic visualization	x	x	x		in rare cases	only in plane	
Multiuser capability	additional AR device	additional AR device	limited	x	x	x	limited

Although AR has the potential to improve the landscape of healthcare with sophisticated health-related information, AR suffers from a variety of functionality and performance challenges. For example, inaccurate images registration, slow tracking data processing, and high computing processing will negatively influence the overall latency of 3D virtual object rendering by which image mismatch would be unavoidable. Image mismatching presents inaccurate presentations of the patients' organs, resulting in incorrect surgical decisions [18]. Also, AR systems will be affected by overall camera calibration, registration and tracking errors, and the accuracy of the users' perception [13]. Other minor challenges exist for the development of AR systems, for instance, user-friendly and intuitive AR interfaces, high development costs, high power usage, and user-friendly

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appearance [24].

2.2   Neurosurgery

Neurosurgical trainees (i.e., junior residents) spend their residency training for a variety of neurosurgeries[2] and building related technical skills (e.g., dexterity) or non-technical skills (e.g., teamwork, communication). The process of any neurosurgery goes through three phases: preoperative (e.g., planning), operative (e.g., intervention), and postoperative (e.g., recovery). The preoperative stage involves creating a blueprint of the neurosurgery's workflow by the application of health-related records and patient-specific imaging studies (e.g., MRI or CT scan) intended to represent patients' medical situations as accurate as possible. Figure 2.5(a) shows an example of the two brain imaging studies, and Figure 2.5(b) shows residents using the imaging studies to plan their next surgical steps. The operative stage involves a set of deliberate surgical interventions. The interventions include navigation or manipulation of tool tasks, for instance, placement of a surgical tool towards a designated nervous region (e.g., eloquent brain tissues) and targeting a specific fracture of the region. The postoperative stage includes a set of steps for complications management and incision closing [8].

2.2.1   Preoperative stage

Traditionally, trainees plan their surgical interventions based on a manual review of patient-specific imaging studies as 2D slices or through 2D displays. The review process

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2. A procedure performed on the brain or the spinal cord or other nervous structures.
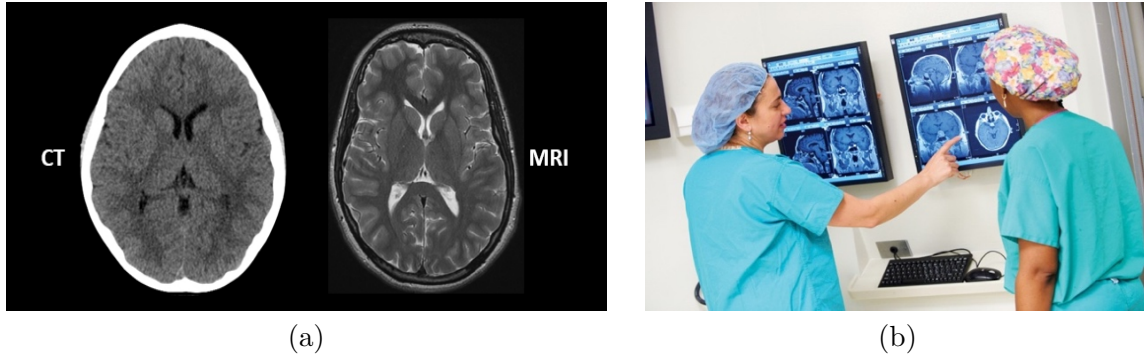
Fig. 2.5: (a) brain imaging studies for CT scan and MRI example (source: http://goo.gl/3WvrpJ), and (b) brain imaging studies are used by residents for planning purposes (source: http://goo.gl/6pA9nB).

is necessary for surgeons to build their own 3D cognitive models of the patients' anatomy and pathology[3] [3][7].

According to Navkar et al. [25], the process of the preoperative stage or planning aims to determine two aspects: a point representing an entrance to the patient's organs and a path towards the nervous region of interest. Eck et al. [26] described the planning process for a neurosurgical procedure as a blend of trajectory preparation and volume exploration processes. Trajectory preparation refers to drawing two 3D points in the Euclidean space within a predefined reference frame. The first position (i.e., target point (TP)) will be located within the region of interest underneath the skin of the head, and the second point (i.e., entry point (EP)) will be located on the outer surface of the skin of the head. The volume exploration process develops the trainee's ability interactively to 1) visualize patients' volumetric and geometric information, 2) control the rendered content, and 3) understand spatial relations between nervous structures in the risky and safe regions and the planned trajectories within them.

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3. A study of diseases' natural and their impact on human being organs regarding structural and functional changes.

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Trainees usually encounter many challenges in accomplishing accurate planning. For example, preoperative planning intensely consumes a deep level of cognitive capacities (e.g., spatial and perceptual) and sensorimotor skills of the trainees in typical situations. The same task will be more perceptually aggressive for trainees in acute situations of patients at ER or OR [12][27]. This phenomenon occurs because trainees usually perform their planning through a mental 2D-to-3D transformation of patient's imaging studies in very limited timespan. The 2D-to-3D transformation is needed to achieve two tasks: 1) to maintain a 3D mental viewpoint of patients' circumstances and anatomy during an operation, and 2) to enable the trainees to apply their medical knowledge based on their viewpoint. Without a seamless 2D-to-3D transformation, trainees are prone to cognitive overload, a potential source for inaccurate decision-making in the OR. Moreover, planning will rapidly change due to possible increasing anatomical changeability, therefore the planning process will go through different iterations whenever patients' circumstances change [3]. Whenever the trajectory changes or is adjusted, by which the TP and EP will change, previous check and recheck step iterations of the risky regions will be invalidated. As a result, the planning process mandates that each trajectory require several iterations of check and recheck steps [26].

2.2.2 Ventriculostomy

Ventriculostomy is a procedure used as a surgical intervention to reduce pressure within a brain structure referred to as lateral ventricular. The pressure occurs as a result of an excessive level of watery fluid referred to as cerebrospinal fluid (CSF). In ventriculostomies,

a trainee performs a set of interrelated surgical steps creating an intrusion into the ventricles. Figure 2.6 depicts an overview of the sequential steps of a ventriculostomy where a resident starts an incision towards a predetermined entry point and inserts a surgical tool (i.e., catheter) to arrive at a designed spot in the patient's brain.

Annually, trainees perform around 300 ventriculostomies within their training periods [11]. The ventriculostomies are crucial to deescalate a variety of acute neurosurgical situations, for instance, hydrocelphis [15], trauma, Reye Syndrome, or subarachnoid hemorrhage [28].
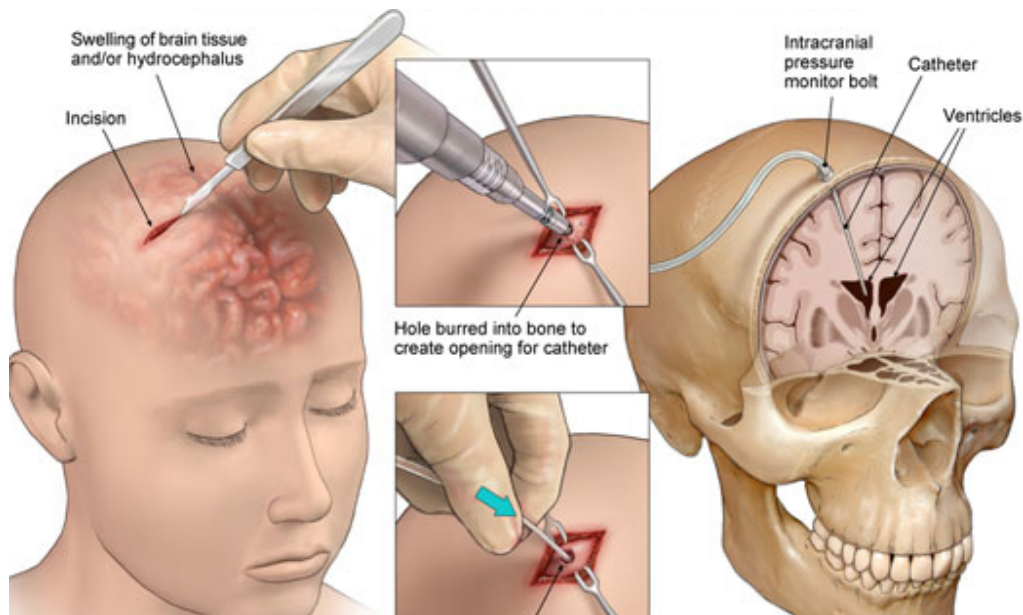
Fig. 2.6: Ventriculostomy procedure workflow (source: https://goo.gl/yB6cCn).

2.2.3 External ventricle drain placement

EVD placement is an important step of any ventriculostomy. EVD placement or ventricular catheter insertion is a targeting task where the trainees need "to choose an appropriate burr hole on the skull and blindly place a catheter through the burr hole to

intersect a lateral ventricle in order to drain cerebrospinal fluid and relieve intracranial pressure." [5]. Figure 2.7 depicts an overview of EVD placement task.

Annually, Srinivasan et al. [28] estimated that trainees perform 25,000 EVD insertions, and it is considered an early and independent task any trainee performs in their academic settings. As a part of their training curriculum, trainees need to develop the targeting skill within the same setting, where they perform it either in intensive care units, OR, or ER.

(a)   (b)
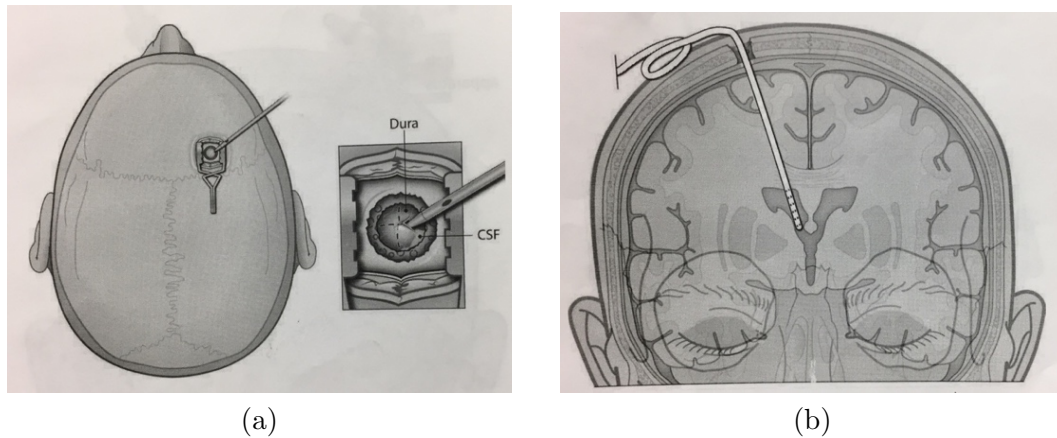
Fig. 2.7: (a) A resident arrived at a predefined entry point and penetrated the EVD's catheter through the dura to extract the cerebrospinal fluid, and (b) the resident passed the catheter which arrived at the bottom of the lateral ventricular [8].

Although EVD insertion is a basic and straightforward task within any ventriculostomy, inaccurate EVD insertions could lead to lethal consequences. Tai et al. [29] stated that the accuracy of freehand catheter placement of EVDs is estimated to be around 22% that land at non-ventricular spaces, even after repeated insertions. Undesired freehand catheter placements will cut through healthy tissues and eloquent brain structures, by which they might traumatize the patient and lead to severe complications. The potential risk of damaging eloquent brain areas is unavoidable when a junior resident

makes multiple hits towards a brain structure by which a set of undesirable trajectories are created [5]. Trainees usually perform EVD placement in the ER with its overarching tasks in sequential stages in active and full systematic analysis capability before acting on patient organs [5].

The deliberate training for the planning process of EVD placement became a necessity. Armstrong et al. [30] stated that EVD placement like neurosurgeries requires trainees to plan a precise trajectory through a designated region on the nervous structures. The trainees will perform their intervention in a relatively narrow fracture within the designated region, which would not be seen by the naked eye. Thus, trainees need to use their cognitive capacities and build a 3D view of where and how to reach to the fracture without damaging other risky regions or eloquent brain areas.

2.3 Surgical Simulators

2.3.1 Types

Simulators are techniques proposed to replicate real situations in fully interactive fashion and immerse users in guided experiences [4]. In other words, simulators are a rehearsal platform to enable trainees to experience a specific situation and to observe and quantify their behavior through the same situation. The primary goal of simulators is to use and assist trainees to maintain surgical skills and get a sense of the same visual and tactile responses as in real cases encountered within the ORs. Surgical simulators emerged as an adequate candidate to fill the gap for an effective means to teach trainees and to

ensure a safe and free-error training environments. According to Kockro [7], "Training with simulators is of obvious advantage, especially in the eye of the patient: we can learn without causing any harm. In neurosurgery, the potential of simulator technology is still massively underutilized."

There are several taxonomies mentioned in the literature about surgical simulators and how they were used for different surgical specialties. A simple form of a surgical simulator is an anatomical-related software package that is running on a stationary computer with a keyboard or a mouse, where a user interactively engages with the projected virtual objects [3].

According to Halvorsen et al. [31], three types of laparoscopic surgical simulators have been used in different surgical specialties: mechanical, hybrid, and virtual. Mechanical simulators are boxes equipped with a digital laparoscope, cameras, screen, surgical instruments, and objects. Similar to mechanical simulators, hybrid simulators are boxes that are connected and monitored by a computer system and sensors. Last, virtual simulators use a combination of a set of digital technologies aimed to allow trainees to interact with 3D virtual objects in an immersive mode and to get objective feedback about their behavior or performance.

Chan et al. [32] argued that there are three types of surgical simulators according to their goals: part-task, full procedure, and surgical rehearsal platform. Trainees used part-time simulators to master a specific psychomotor subtask, as it was split from a set of chronological surgical tasks. Full procedure simulators are designed to replicate multiple sets of chronological surgical steps that mimic real cases encountered within the ORs. Also, surgical rehearsal platforms - more complicated simulators to build than the

previous two types - are designed to thoroughly engage trainees in a virtual environment by presenting fused surgically-relevant environments in which to practice technical and non-technical-related skills.

In the neurosurgical context, [33] discussed that there are five groups of surgical simulators used in neurosurgical training: computer\VR simulators, cadaveric models, in vivo models, synthetic models, and living patients. Cadaveric and in vivo models include dead animals used for anatomy studies, and synthetic models use sensor-based mannequins that are connected to computer machines [34].

With advanced and low-cost VR\AR technologies, development of simulation-based training gained more attention from medical researchers. With appropriate contextual information throughout a neurosurgical procedure using AR\VR facilities, senior residents and trainees gain a real-time view of specific anatomical segments that were fused upon patient's organs from different modalities. It is most likely that trainees will be very efficient at their practices with the use of AR\VR visualization modes because they depicted a synthesized version of "anatomic, metabolic, and functional data" from different sources about a specific patient situation. Also, the visualization mode could also be examined in detail, distributed and discussed with trainees and other peers and research community [3].

2.3.2 Motivation of simulation-based surgical training

Currently, hospitals and residency directors have been pushing towards simulation-based residence training programs as a supplement for new trainees to cope with conventional

surgical teaching method challenges. The apprenticeship model is a classic surgical teaching method where trainees attend senior residents' live surgery sessions to observe and practice on live patients during the surgery.

According to McGaghie et al. [35], it has been shown that training based solely on the apprenticeship model produces inferior results without supplementary simulation techniques. The apprenticeship model is not efficient enough because it consumes a massive amount of hospital resources in terms of money and time. The costs include the costs of actual surgeries from OR operating fees until a complete surgical team [4]. Moreover, trainees usually suffer from lack of real-time feedback during the apprenticeship model, as it would take up to a month for the decision to confirm or reject the surgery performance to appear by the patient's recovery stage. The apprenticeship model is not flexible; it imposes a variety of restrictions on senior residents. Senior residents usually have 80 hours of deliberate practice a week to fulfill, but senior residents never exceed 5 hours of deliberate practice a day with full cognitive capacities [4]. Because the apprenticeship model necessitates the attendance of senior residents to training locations to supervise trainees, trainees would observe only a handful of ventriculostomies to maintain their skills, and the trainees need to use their own judgment for new or rare neurosurgical situations. As a result, trainees might not achieve the expert level within the given residency training timespan [4].

By the applying simulation-based training as a supplement, hospitals would utilize customized simulator systems to recruit as many trainees as possible with a given time needed for the deliberate training. Consequently, hospitals can reduce the usage load on ORs and the surgical team for real procedures. Trainees most likely would commit

fewer surgical errors, a contributing factor for collateral damage or threat to patients' safety. Simulation techniques will enable trainees to have adequate surgical practice anywhere and anytime. Also, trainees will receive autonomous surgical training that not only involves a variety of surgical techniques, anatomies, and pathologies but also offers necessary tools to support different surgical specialties and to increase procedures' success rates [7][12][4].

2.3.3 Simulator validation

Simulator validation is a process in which a particular test or metric measures a specific aspect of a simulator [15]. One of the primary challenges to developing valid surgical simulators is to engage trainees in the complex dynamics of real surgical scenarios including patients, senior residents, and interconnected surgical steps that occur during the surgical procedure. Many surgical simulators did not last; either they are not sufficient to support enough scenarios in ORs, or they might be seen as a valid option according to subjective evaluation techniques [3].

Several validation approaches have been followed to determine the validity of surgical training tools. Kirkman et al. [33] and Dankelman [36] indicated that three groups of validation approaches for surgical simulators would include written and oral examinations (e.g., feedback surveys from users), live observation of evaluators or simulator-derived metrics or a blend of both, or written tests intended to assessment users' knowledge after the use of the simulator systems. Johns [4] and Armstrong [15] stated that psychometric tests or evidence have been used to assess reliability and validity of surgical simulators.

Psychometric evidence includes face, content, construct, concurrent, and predictive validity tests. A face validity test is concerned with how a simulator will measure what it is supposed to measure from the perspective of experts. A content validity test evaluates the extent a simulator will measure all relevant content or properties of a specific surgical task or procedure based on a checklist or expert opinion. A construct validity test determines the extent a simulator measures a particular trait that the simulator is claimed to measure. Construct validity is most common assessment technique used and is well-documented to quantify the psychometric competency between senior and junior residences in the literature. A concurrent validity test is concerned with how a simulator will comply with well-defined standards for a surgical task or procedure. A predictive validity test concerns how a simulator can predict trainees' performance in the future through real surgical scenarios.

2.4   User learning process

Learning is a process by which a user acquires a new knowledge, skill or behavior. Practicing a skill for a long time would be necessary to accomplish a competency level in it. For some disciplines, a human could master a particular skill after a long time of intense training [37]. For example, a chess player needs nine years to obtain master status. Even in common folklore from a variety domains such as music, it takes a violinist around 10,000 hours of deliberate practice at the age of 20 to master his or her skills [4].

Figure 2.8 provides a graphical representation of the learning process curve phenomenon and the trade-off between competency or performance and experience. With

continuous practice, users learn a variety of everyday tasks until the tasks do not require much cognitive input from them. Then, users would become autonomous, and no performance increase is observed. Some professionals reach an advanced level of skill and stop continuing to improve, a situation referred to as arrested development [4].
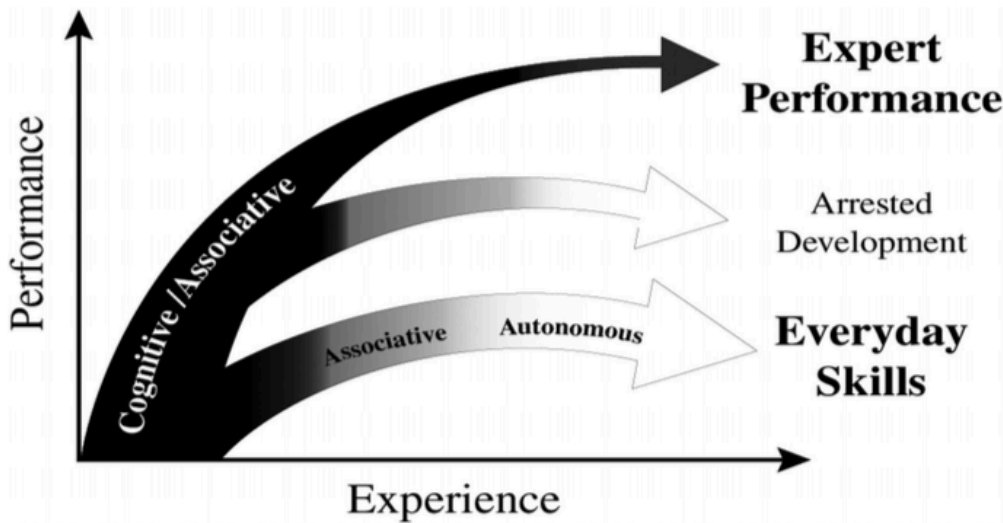
Fig. 2.8: The relationship between cognitive efforts, experience, and human performance during users' learning process [38].

In the surgical context, because trainees spent 12 to 13 years in medical schools, it is expected trainees will develop the necessary skills with many hours of deliberate practice on live patients, including supervised and intraoperative training. In reality, trainees might not have cultivated the required mastery of specific skills [4].

According to Armstrong [15], mastery of a skill depends not only on the amount of deliberate practice but also the use of cognitive effort in the surgical context, which is depicted in Figure 2.8. Cognitive processes, visuospatial reasoning, and immediate and informative feedback are a few contributing factors that influence users' learning curve in the surgical training context. Cognitive processes (e.g., perception, decision

making, depth perception) are fragile against how studying images were represented and how trainees will interact with them. The more stimuli[4] exist within the OR, the better residents could maintain perception and decisions during their training. Visuospatial reasoning will enable trainees to form a mental perspective about the current nervous structures for further surgical tasks [15]. The immediate and informative feedback could include two types: active and passive. The former type is under computer system control, such as visual or audible notifications, while the latter type emerges as an internal sensation within the user's body [39].

2.5 Human-computer interaction

Human-computer interaction (HCI) is a technique by which a user accomplishes a task for a specific interface conceptual model and receives a specific feedback [39]. User interactions towards a system display take few styles: text entry, menu selection, navigation, and direct manipulation. Direct manipulation is intended to allow users to recognize an object of interest in the user interface and to perform a particular function directly before observing the effect [40].

2.6 Perception depth in surgical training

Among other cognitive processes, the depth perception process includes how trainees observe the effects of their actions with a display screen and reconcile these effects. The

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4. Stimuli could be visual, auditory, or tactile feedback, such as a physical sensation of the surgical tools and their interaction with the tissue. [15]

trainees decide to perform a surgical task based on the interaction outcome between their cognitive processes when interacting with a visual stimulus and its background. Inaccurate depth perception is a common problem since low modality resolution and blurry displays cause 3D virtual objects to appear further away from their predetermined location against the physical objects, a contributing factor to user axis bias and misjudgment of users' movements. Trainees could perform complex psychomotor tasks or improve their performance by effectively predicting the depth of a target features [15].

A 3D-based user interface enables users to visualize and consume 3D objects in Euclidian dimensions (i.e., X-axis, Y-axis, Z-axis), that includes the depth dimension. For the users to complete their 3D tasks (e.g., navigation or manipulating 3D objects) through 3D-based user interfaces, it is important that users gain an understanding of the dynamic of depth perception of 3D objects and tasks and functionality of the human visual system [41].

Depth perception depends on two factors: distance judgment and visual depth cues. Distance judgment requires the users to maintain a mental interpretation of the physical objects around them and how close or far the objects are. A visual depth cue is a synthesis of an image's feature, used to convey a sense of depth dimension, and functionality of the human visual system. Figure 2.9 depicts an overview of common visual depth cues.

Bowman et al. [23] stated that visual depth cues are categorized into four groups: monocular, oculomotor, motion parallax, and binocular disparity and stereopsis. Monocular or object-centered cues [41] are when a user through a single eye uses a static image's

features (e.g., relative size[5], occlusion[6], or linear perspective[7]) to yield depth information [41]; these techniques are depicted in Figure 2.9(a) and Figure 2.9(b), respectively [23].

Oculomotor or observer-centered cues [41] involve muscular tension from the user's eye while they are looking at a set of objects from a certain distance. Whenever their eye muscles relax and the eyes' lenses become more spherical, then the users see objects as far away. This phenomenon is referred to as accommodation. Another oculomotor cue is referred to as convergence, the rotation of users' eyes when the eyes converge and diverge when looking at near or far objects, which are depicted at Figure 2.9(c), respectively, [23].

Motion parallax or dynamic depth cue is a phenomenon that occurs when users look at a set of stationary objects during their physical movement around the objects; the users see the objects moving relatively quickly if they are close and relatively slowly if they are far; these are depicted in Figure 2.9(d) [23].

Binocular disparity and stereopsis refer to the extent a user sees an object using two eyes, by which a difference representation occurs and yields two different images of the same object. The greater the fusion of the two images, the more the users will able to determine how close the object is from his\her eyes Bowman et al. [23].

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5. The relative size phenomena is about sorting a set of objects in a way that the user sees the smaller is the object, the more the object appears to be farther away.

6. Occlusion is a phenomenon of sorting a set of objects in a way that the user sees the first object as opaque and occludes another object. Then, the user will see the first object as closer to him\her than the other object

7. Linear perspective is a phenomenon of sorting a set of objects in a way that the user sees both objects marked with parallel lines. Then, the user will see that the closer to each other the parallel lines get, the farther the objects will appear to the user.
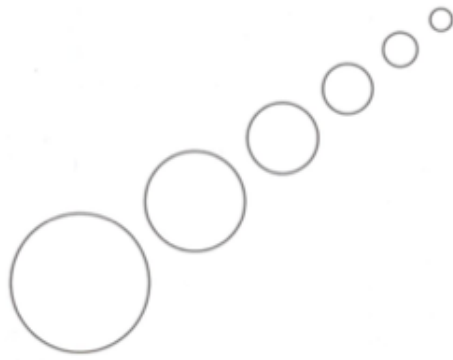
a) Relative size.
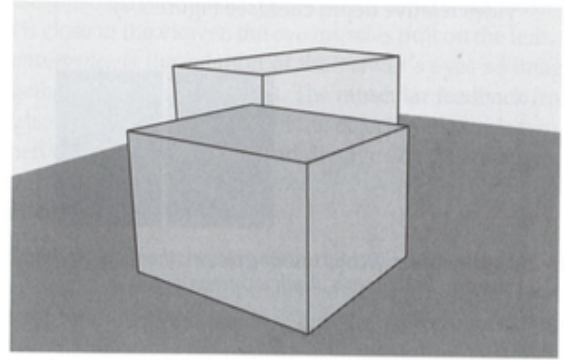
b) Occlusion and linear perspective.
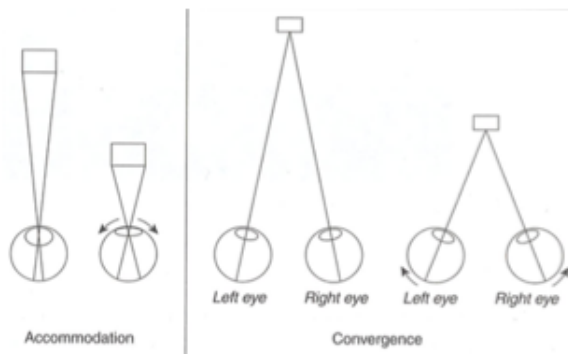
c) Oculomotor (Accommodation, Convergence).
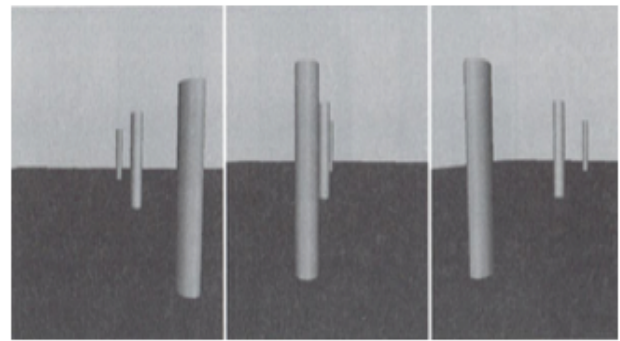
d) Motion parallax.

Fig. 2.9: Overview of common visual depth cues [23].

2.7 User performance assessment

2.7.1 User performance

According to Wickens et al. [41], task performance for a user is a result of three processes: gaining a perception about a task, making a decision about the task, then committing an action towards the task completion. The first process concerns how the user's brain system will perceive the received messages from the user's senses. The received messages are intended to form a piece of information necessary for the coming stages. The second process is concerned with how the user decides what to do with this information. The

third process involves how the decisions will be carried out.

As interactions between humans and computer systems evolve and the latter become increasingly complex, there is a need to analyze human cognitive processes within these interactions [42]. Such analysis is a crucial aspect of measuring users' performance of tasks accurately. Conventional task analysis approaches do not focus on analyzing and representing the human performance through cognitive processes. Task analysis approaches usually pay more attention to physical or observable aspects of the human performance of tasks.

In the surgical context, a surgical procedure is a combination of generic and advanced surgical tasks that require a certain surgical competency level (i.e., technical, team performance, and communication and decision-making skills). The evaluation of trainees' performance usually focuses on their surgical competency. Surgical competency is based on a hierarchy of simple psychomotor tasks, for instance, navigation of a tool towards a specific target or manipulation of a physical object [15].

Assessment of surgical competency for surgical procedures is a challenging goal. The difficulty of such assessment comes as result of not only inefficiency of traditional assessment methods but also the complexity of analyzing and representing the cognitive processes within the human performance of tasks. Traditional evaluation methods depend on subjective experts' opinions, unstructured long-duration analysis tasks, or possible unavoidable unnecessary iteration processes when creating these assessments [43].

2.7.2 Hierarchical task analysis

A new trend towards a structured assessment technique has been used towards an understanding of surgical procedures. The technique is referred to as hierarchal task analysis (HTA). HTA technique is a process intended to help analysts to determine the source of errors of a system performance (e.g., human performance) and to propose solutions for the same system [44]. HTA technique is built on the idea of a decomposition of a system's goals. Goal decomposition is a process in which an individual goal and its current states are identified through breaking them down to sub-components in a hierarchy [44]. HTA has been used in a variety of studies evaluating surgical procedures or techniques [45][46][47]. Table 2.2 depicts an example of surgical HTA—tabular format—for a task in performing an open inguinal hernia repair [48].

Tab. 2.2: An example of a task in performing an open inguinal hernia repair task with its subtasks and possible recovery steps that lead to the successful completion of a procedure [48].

No.	Task	Plan	No.	Sub-Tasks	Recovery
5	Open up inguinal canal	Do subtasks 5.1, 5.2, 5.3, 5.4 in consecutive order	5.1	Small incision transversely on external oblique aponeurosis in line with external ring	
			5.2	Incision extended laterally and medially releasing external ring	
			5.3	Superior and inferior leaves dissected off and clips applied to each leaf, lateral pocket formed	
			5.4	Travers retractor inserted in between superior and inferior leaves	Travers retractor comes off, reapply retractor

Although HTA construction may take few months of practice expertise and practice to effectively administer under expert guidance, HTA is flexible in describing a system, and it can be tailored to fit a variety of situations and needs (e.g., team performance assessment, human training requirements) [44][42].

2.7.3   Fitts' law

User performance evaluation is a key aspect of the validity of any solution in the context of surgical simulations. Following the work of information theorist Claude Shannon in evaluating of communication systems' capacity, Paul Fitts extended Shannon's Theorem 17 [49] to accommodate measuring simple 2D psychomotor tasks in human behavior to determine the human capacity to fulfill the tasks. Shannon's Theorem 17 is summarized as equation 2.1:

$$C = B \log \frac{S + N}{N} \tag{2.1}$$

Where C is human capacity (in bits\s), B is bandwidth (in 1\s or Hz), S is a single power source, and N is a noise power [50]. Fitts' model or Fitts' Law [51] aims to measure the information capacity of the human motor system through quantitative-based metric referred to as the index of performance (IP). MacKenzie [50] discussed Fitts' Law as follows:

> The realization of movement in Fitts' model is analogous to the transmission of information. Movements are assigned indices of difficulty (in units of bits), and in carrying out a movement task the human motor system is said to transmit so many bits of information. If the number of bits is divided by the time to move, then a rate of transmission in bits per second can be ascertained.

In Fitts' Law, both signals and noise correspond to amplitudes (A) and move

width (W), where the former represents movement distance of the human and the latter represents the width of the region within which a movement terminates. IP is calculated through two approaches. The first approach involves dividing a motor task difficulty or the index of difficulty (ID) by the averaged movement time (MT) over a block of trials to complete a motor task. The second approach involves a regressing line MT on ID, where MT is the dependent variable, and ID is the independent variable. In the first approach, IP is calculated as eq. (2.2)

$$IP = \frac{ID}{MT} \tag{2.2}$$

Where ID is calculated as eq. (2.3):

$$ID = \log_2 \frac{2A}{W} \tag{2.3}$$

In the second approach, IP is calculated as the regression line as eq. (2.4):

$$MT = a + bID \tag{2.4}$$

Where a and b are regression coefficients. The reciprocal of the slope coefficient, $\frac{1}{b}$, corresponds to IP. The usual form of Fitts' Law in the second approach is calculated as following in eq. (2.5):

$$MT = a + b \log_2 \frac{2A}{W} \tag{2.5}$$

2.8   Summary and Conclusions

In this chapter, background on AR surgical simulation is provided. In next chapter, an overview of related AR surgical simulation tools for EVD placement training and planning aids will be discussed.

Chapter 3

Related Work

3.1 Introduction

Across surgical disciplines, simulators have been used by novice trainees for image-guidance, deliberate training, and planning aids. In AR based systems, the main motivation for surgical simulators is to allow trainees to master an individual task or subtask, the steps of a set of procedures or a wider range of neurosurgeries within predefined certain surgical scenarios, keeping patients safe from any harm from actual training trials [4][52][32][53].

Although neurosurgical simulation has had the attention of the research community for a while, many of the available AR simulation tools either act as one-size-fits-all procedures, or they lack well-defined validation metrics. Designing simulators for a patient-specific task and validating the users' performance based on objective metrics is a challenging goal. To our knowledge, many AR simulators designs do not survive clinical settings due to validation or usability issues. According to [54], seven common guidelines exist for an AR system implementation. Any AR system ought to 1) have an intuitive user interface, 2) minimize mental transformations of users between different coordination systems, 3) be plug-and-play to reduce its workflow intrusion, 4) take

small or almost-no space in the OR, 5) offer a similar experience to the previous systems, 6) support micro and macro views of the workspace, 7) be transparent to the users in terms of errors or loss of tracking, and 8) show a real visual representation of the actual used tools and workspace. This chapter sheds light on related work to the ventricular catheter insertion task (refer to section 2.2.3) for ventriculostomies (refer to section 2.2.2) simulators for deliberate training and planning aid for novice neurosurgery trainees.

3.2   Web-based simulation

One of the early simulation works on the ventricular catheter insertion task was proposed by Phillips and John [53]. The authors proposed a web-based Java program envisioned to be used as a part of formalizing surgical training. The program lets trainees practice the task through a personal computer (i.e., 2D display screen and a mouse) connected to the internet for training and planning. The trainees would be able to practice the task, see visual feedback, and learn the associated anatomical structures. On one hand, the program was free and platform-agnostic, and it did not require expensive or complicated hardware. The program exposed trainees to a variety of simulation settings, for instance adjusting the size of the workspace and possible entry points. On the other hand, the task required the users to be and interactively engage in a 3D environment with the virtual patient and the interest region, which is hard for a 2D display screen. Moreover, the authors did not report the evaluation of the user performance or define formal or validation metrics.

3.3 Neuronavigation-system-based simulation

With neuronavigation systems, for instance, Krombach et al. [55] and Kirkman et al. [56], few efforts were considered for the simulation of the ventricular catheter insertion task. Krombach et al. [55] evaluated the EasyGuide neuronavigation system for training and planning. The system enabled trainees to plan the task based on a pointer, self-adhesive external fiducials, virtual MRI images from 29 patients, and a live patient at the OR. The system was easy to set up, accessible within any OR, and user-friendly and intuitive. Nevertheless, the system indicated that inconsistent results with common wisdom where senior residents were not accurate enough compared to trainees. The system also could not help trainees with enough feedback by determining their accuracy or the length of the system's pointer. Kirkman et al. [56] evaluated the use of Medtronic StealthStation neuronavigation system for the planning stage of the task. The system supported trainees to plan the task based on an electromagnetic-based device in a screen display, using a hollow resin model head and a catheter. The system measured trainees' performance based on a firm validation plan, where they considered objective metrics (i.e., stress and workload) and subjective measures (i.e., pre and post-test questionnaire). The system, however, used a fixed entry point and catheter depth, which limited the trainees' ability to practice and experience a variety of surgical scenarios. The system setup also would consume more time to perform the task, a disadvantage for the workflow of the catheter insertion task. The authors did not discuss the possibility to scale up their work for a variety of surgical scenarios.

3.4 Mixed-reality-based simulation

Customized AR\VR modules, mounted to mechanic simulators, were built for the simulation of the ventricular catheter insertion task. Luciano et al. [57][6] proposed an AR physical-based simulator, referred to as ImmersiveTouch, for the training of ventriculostomies, especially for visual-haptic feedback. The simulator processed real imaging studies (e.g., CT and MRI scans) to create a patient-specific visual and tactile representation. The simulator was based on a half-silvered mirror, haptic stylus, and head-and-hand tracking systems. The half-silvered mirror was used to construct and visualize an AR scene, while the haptic stylus was used to construct and visualize a virtual catheter and to render a visual and tactile feedback. The head-and-hand tracking systems was used to ensure an accurate image projection between the virtual catheter and the haptic stylus. The AR scene included the trainees' hand, the virtual catheter, and the virtual patient. The simulator was intended to help trainees to define an ideal catheter trajectory, to measure their performance for the targeting task, and to render the final coordination of the catheter in the 3D world. Yudkowsky et al. [58] evaluated the ImmersiveTouch simulator for 16 trainees through 15 virtual meshes of real patients' brain with a variety of ventricular shapes for the training and anatomy education. The authors evaluated the trainees' performance based on objective and subjective metrics. Although the system demonstrated an improvement in trainees' performance before and after real surgical interventions, the simulator limited the surgical scenarios to a fixed entry point towards the 3D virtual nervous structures. The simulator also needed more improvement regarding object-to-object collision detection. Moreover, a major issue of the system was that

trainees performed their tasks with inaccurate depth perception of the virtual catheter, a technical problem that would lead to health complications in a real clinical setting.

Kramers et al. [59], Armstrong et al. [30], and de Ribaupierre et al. [5] designed and evaluated two AR module prototypes for targeting surgical tasks for tumor resection and ventriculostomies for planning and training. The authors designed their prototypes as extensions for a surgical VR simulator referred to as NeuroTouch or NeuroVR [60]. The AR modules were based on Android-based modalities, a stereovision system, a high-end computer, a static physical mannequin head, a haptic device that offered haptic tracking, leg pedals, and NeuroVR proprietary simulation software. The former AR module allowed trainees to target a specific feature of the 3D virtual nervous region, and the last AR module allowed trainees to target a complete segment of the brain region. Both AR modules deployed in handheld devices (smartphone, tablet) to not only align virtual information upon a mannequin's head but also render the trainees' trajectory, internal anatomy, and the entry point corresponding to a clinical scenario. Tactile and visual feedback for assessment of technical skills were recorded based on objective metrics. Using the AR modules, the trainees showed better performance tasks through the early prototype. During the training sessions, the trainees, however, suffered from a steep learning curve. The inaccurate judgment of targets depth resulted from 3D meshes' occlusion with the mannequin head, lighting discrepancies, and conflicting visual depth cues. Although the AR modules allowed for patient-specific scenarios, the performed targeting tasks by the participants were limited to only single predetermined spot (i.e. 3D virtual entry point) of the mannequin head and interacting with the virtual nervous structure in a narrow movement arena. It is highly possible that trainees need to use

different entry points to the interest region with a different hand or direction, and it is most likely re-planning the process of the targeting task would occur if the trainees had uncertainty about the task.

Hooten et al. [61] evaluated a mixed-reality simulator, designed to educate neurosurgical trainees to perform complete ventriculostomies. The mixed-reality simulator included 3D-printed concepts of the brain anatomy and a VR system. The system allowed for visual and haptic feedback and the trainees' performance was measured based on a scoring algorithm by combining time and accuracy. Although the simulator was designed for complete ventriculostomies, the simulator could not adapt for possible and rapid scaling up for patient-specific anatomies with a variety of surgical scenarios, for instance, for slim or shifted ventricles.

Lee et al. [62] evaluated a simulator for the training of a catheter insertion task, referred to as Dextroscope, with different entry points and approaches. The authors performed the tasks on only 10 cases with normal-size ventricles for the adult population, and they did not report a comprehensive validation plan for their module regarding usability or user performance.

3.5 3D-printing-based simulation

Other efforts considered ventricular catheter insertion simulation through the usage of 3D-printed concepts. Tai et al. [29] and Ryan et al. [63] designed and evaluated a couple of 3D-printed surgical phantom heads intended to allow trainees to perform a set of steps of ventriculostomies, including a ventricular catheter insertion task for the purpose

of training with tactical feedback. On one hand, the trainees were able to assemble the 3D-printed inner parts for the purpose of anatomical knowledge, and the simulators enabled the trainees to adjust the inner parts of the phantom heads to accommodate a set of patients' cases. Both systems also focused on haptic feedback and brain tissue deformation. On the other hand, both phantom heads did not provide a planning mode to practice or measure the accuracy of catheter insertion or the perception of created trajectories. In addition, the authors did not use objective evaluation metrics to avoid any possible user bias about their performance. Using 3D-printed simulators might be an affordable approach to expand access to basic ventriculostomy training, although, for rare or totally new neurosurgical situations, it might be costly to maintain 3D-print phantom heads for every neurosurgical situation.

3.6 Handheld-modalities-based simulation

Handheld or portable modalities have been used for the application of targeting tasks simulation. Deng et al. [64] proposed a mobile app installed on a tablet-AR modality, that was connected to a locally developed neuronavigation system through a wireless local area network. The modality rendered AR-generated information on its screen based on the navigation cues from the neuronavigation system. The system was designed to enable senior residents with image-guidance capabilities to observe patients' anatomy for tumor resection procedures. During the surgery, the modality gave neurosurgeons the ability to frequently switch views between its virtual scene and the physical view. However, the system required the neurosurgeons to hold the modality by their hands during the

surgery, which would limit their cognitive processes (i.e., decision making) and movement. Also, the system had a number of functionality issues, for instance, long software latency would lead to noticeable virtual meshes alignment error, and as a result, registration, tracking, and camera calibration errors. Eftekhar [65] proposed an Android mobile app installed on a smartphone, referred to as Sina, intended to provide a simple means for intraoperative neurosurgical planning for a catheter insertion. The simulator allowed the senior residents to load previously processed imaging studies (e.g., CT and MRI), and the residents could manually project the smartphone onto a specific patient's organ to overlap the processed images on it. Using the simulator, the residents would see a relative position of the catheter entry point based on the imaging studies loaded. Although the simulator could maintain image-guidance and continuous monitoring during the catheter insertion in a simple way, there are few usability and validation issues with the app. The simulator provided a static view of image studies in which it is difficult for the residents to have precise overlapping, to recheck the task-related landmarks or the entry point as soon as they rotate their heads. Because the simulator requires another user to hold the phone for the original residents, whenever the surgical team encountered an ineffective communication situation, the planning process eventually would take a longer time due to the imprecise overlapping of imaging studies. In addition, the simulator did not undertake a comprehensive validation approach to measure their trainees' performance.

3.7   Summary and Conclusions

An ideal AR-based system for ventricular catheter placement simulation for training and planning aids should include a variety of attributes. The system has to engage a user in the 3D environment by offering a 3D user interface. The system needs to cope with the high computation demand of AR information projection, yet the system should not suffer from a long system latency. The system should not limit the input in surgical scenarios regarding lateral ventricular size, entry point position or orientation, or length of the catheter. Also, the system should provide users with visual feedback about their task, and the system should support visual depth cues to lessen the hurdle of inaccurate depth perception. Moreover, the system should enable the dynamic mobility of a trainee's whole body or some part of it around the patients. Also, the system should measure and record users' performance according to their accuracy and speed to complete the task without affecting their workflow.

In this chapter, an overview of related AR surgical simulation tools for EVD placement training and planning aids is discussed. In next chapter, a detailed discussion about the development of AR simulation modules for EVD placement tasks using MDE will follow.

Chapter 4

Design of Augmented Reality Training and Planning Aid Simulation Modules for EVD Placement Using Model-driven Engineering

4.1 Introduction

The use of image-guidance systems (e.g., navigation or planning systems) for complex neurosurgical procedures in ORs became popular when they included appropriate contextual information [59]. These systems have been used: 1) to fulfill surgeons' need to see

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- This work has been published as:

    - H. Ghandorh, S. De Ribaupierre, R. Eagleson, "Development of Augmented Reality Training Simulator Systems for Neurosurgery Using Model-Driven Software Engineering", *IEEE 30th Canadian Conference on Electrical and Computer Engineering (CCECE) [Computer and Software Techniques Track]*, April 2017, Windsor, Ont, Canada.

    - H. Ghandorh, S. De Ribaupierre, R. Eagleson, "An Augmented Reality-based Platform for Users' Training and Performance Assessment for Neurosurgical Targeting Tasks", *The 9th annual International Conference on Education and New Learning Technologies*, July 2017, Barcelona, Spain.

real-time patients-specific imaging studies with improved medical diagnoses, and 2) to enhance their cognitive abilities when performing a surgical intervention prior to reducing surgical errors [59][17].

Development of neurosurgical simulation tools for medical education and training purposes is a non-trivial goal. Typical neurosurgical simulation tools use sophisticated equipment and require technical setup and expertise to prepare and operate. Image registration, camera calibration, 3D surface rendering of imaging studies, object tracking and other technical requirements are necessary, including diverse underlying platforms for deployment and wider user landscapes [59]. In addition, the influence of human factors (human perceptual, motor, and cognitive capacities) play a critical role when designing such tools [12]. Moreover, many resources dedicated to simulation systems design and development are wasted in trial-and-error attempts due to inaccurate representations of clinical settings. In addition, a major requirement of such tools is that the tools need to follow a thorough validation process. Therefore, the typical development process will not be able to deliver such tools in low man-hour budgets.

Model-driven engineering (MDE), a software development vision, focuses on modeling transformations and technologies to simplify and formalize various software development activities [66]. MDE promotes the transformations of abstract models as the primary activity in the development life cycle prior to producing executables within a particular domain and set of rules.

Several techniques have been proposed to embody the vision of MDE, for instance, model-driven architecture (MDA), agile MDE, domain-specific programming, or software factories [66].

Following the MDE vision, developers will be able to deliver executables while hiding complex platform details, reducing manual coding errors, and allowing the sharing of experts' knowledge in a specific domain [67]. As a result, high-quality executables could be delivered more frequently in shorter timespans.

This chapter fulfills the first aim of our research study, and it describes the extent to which MDE is a suitable development approach to generate two AR simulation modules[1]: 1) stationary module (i.e., desktop version) , and 2) portable module (i.e., smartphone app). The purpose of the locally developed AR simulation modules is to enable users: 1) to visualize AR information needed as training and planning aids for an EVD placement or insertion task (refer to Section 2.2.3), 2) to enable users to practice the EVD placement with predefined surgical scenarios, and 3) to enable domain experts or evaluators with a mode of assessment to measure novices' performance as a trade-off between speed and accuracy.

4.2 Methodology

4.2.1 Our MDE-based approach

We adopted the MDA technique, a well-documented and most common technique for MDE-based development. Figure 4.1 presents a comparison between a typical software development life cycle and MDA development vision.

MDA entails three main milestones: 1) crafting of platform-independent models (PIMs), 2) crafting of platform-specific models (PSMs), and 3) building of code genera-

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1. The terms AR simulation modules or generated executables will be used interchangeably.
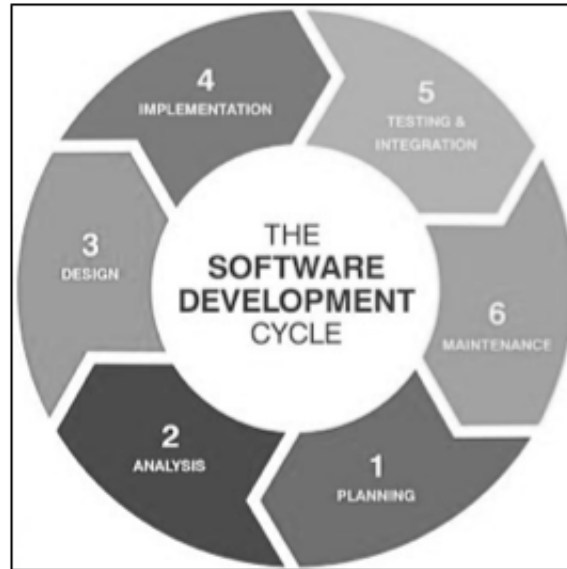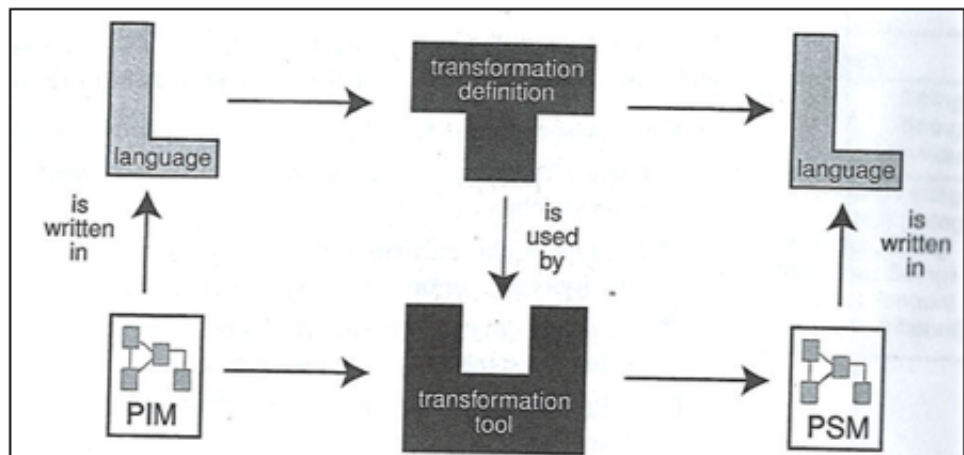
Fig. 4.1: Typical software development life cycle vs. MDA development vision [68].

tors. PIMs are domain-related specifications that should be modeled in a formal modeling language (e.g., United Modeling Language (UML) profile). PSMs, which are derived from PIMs, are platform-related specifications. Both PIMs and PSMs are created by modeling tools, and PSM will be used as the input for a code generator, a component intended to source code production that complies with a particular set of domain rules [67].

Figure 4.2 indicates an overview of our approach to fulfilling the MDE vision of the development of the two AR simulation modules or the generated executables.
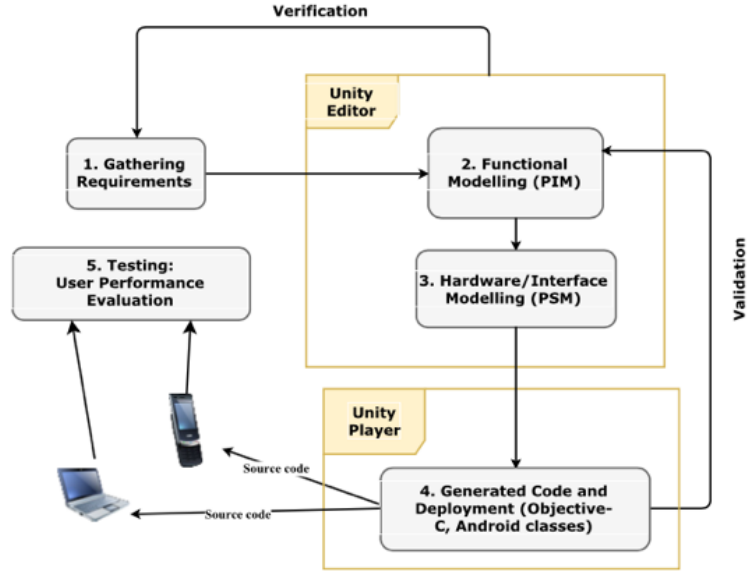
Fig. 4.2: A simplified flowchart of MDE-based approach.

First, we identified a set of requirement specifications (Figure 4.2(1)). A neurosurgical scenario, the input for AR simulation modules, includes a description of an EVD placement trial. Figure 4.3 depicts an example of a neurosurgical scenario for EVD placement within a ventriculostomy procedure (refer to Section 2.2.2), represented in Harel statechart notation. The neurosurgical scenario is represented as surgical HTA (refer to Section 2.7.2) in a bullet-point format. A portion of the neurosurgical scenario is presented as follows:

- Phase 0: Review imaging studies (CT scans or MRI).

- Phase 1: Localize the closest entry point in the right frontal bone in the skull to the lateral ventricles.

- Phase 2: Visualize the shape and location of lateral ventricles in your mind.

- Phase 3: Orient your EVD to be in line with the best trajectory.

- Phase 4: Advance the EVD towards the lateral ventricles until you hit the frontal horn :

  - Penetrate the EVD's catheter through the inner table of the skull bone perpendicularly to the brain surface slowly to $<= 6$ cm depth.

  - The stylet then is removed and the catheter is kept in the burr hole.

  - A slight pop in resistance emerged (i.e., increase resistance than a loss of resistance).

  - When the frontal horn is cannulated, CSF drainage should emerge through the catheter.

We focused on the Phase 4.1 step from the scenario that fulfills the required EVD placement targeting task. Listing 4.1 depicts an example of textual description of the EVD placement task in JavaScript Object Notation (JSON) tags format.
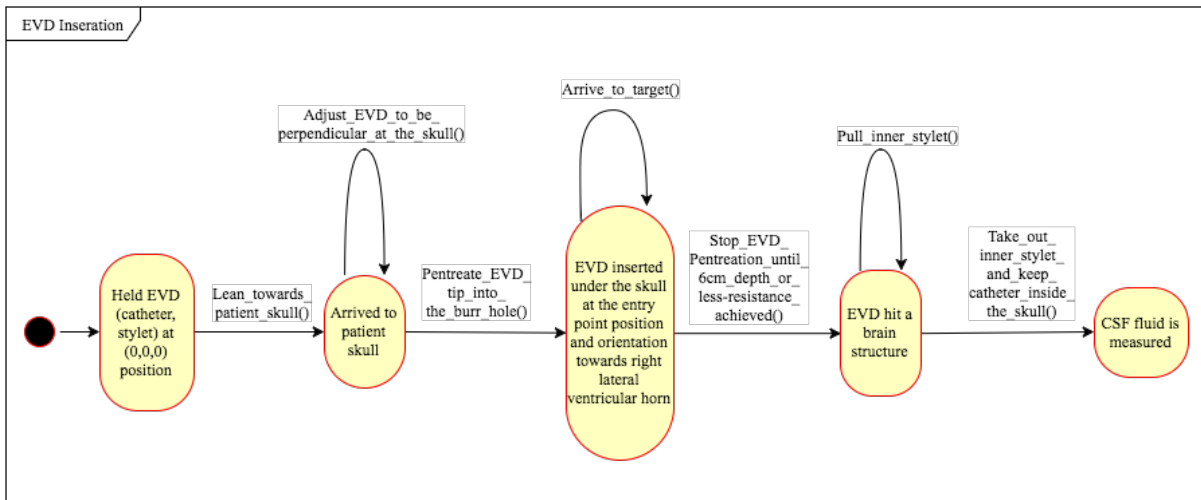
Fig. 4.3: A surgical scenario of the EVD placement task in Harel statechart notation.

Listing 4.1: A surgical scenario the EVD placement task in JSON tags

50

```
{

"id": "413a41e3-ce7d-4d18-904c-411f53ccca0e",

"name": "Demo Targeting 1",

"assets":

 [{

        "tag": "Target 1",

        "position": { "x": -6.45441866, "y": 0.5490153, "z": 1},

        "rotation": { "x": 0, "y": 0,"z": 0},

        "scale": {"x": 1.23174512, "y": 1.23174512,"z": 1},

        "assetId": "00000000-0000-0000-0000-000000000000"

 }]

}
```

The neurosurgical scenario was maintained and came from a third-party system (i.e., ScenarioSim) that facilitated the transformation of the textual description of the oral description of the neurosurgical scenario from a domain expert (i.e., senior neurosurgeon). Then, we maintained visual representations (i.e., PIM) of the AR scene and verified them with the domain expert during the designing of both systems. The visual representations were then designed through the editor of Unity (Unity engine 2017.2.0 Educational, Unity Technologies, San Francisco, California, USA) (Figure 4.2(2)). The Unity editor is a game engine editor intended to create and model game scenes including 3D interactive objects, which is depicted in Figure 4.4.

Whenever the AR scenes were completed and particular configuration settings were adjusted, Unity libraries transformed the current visual representations to platform-
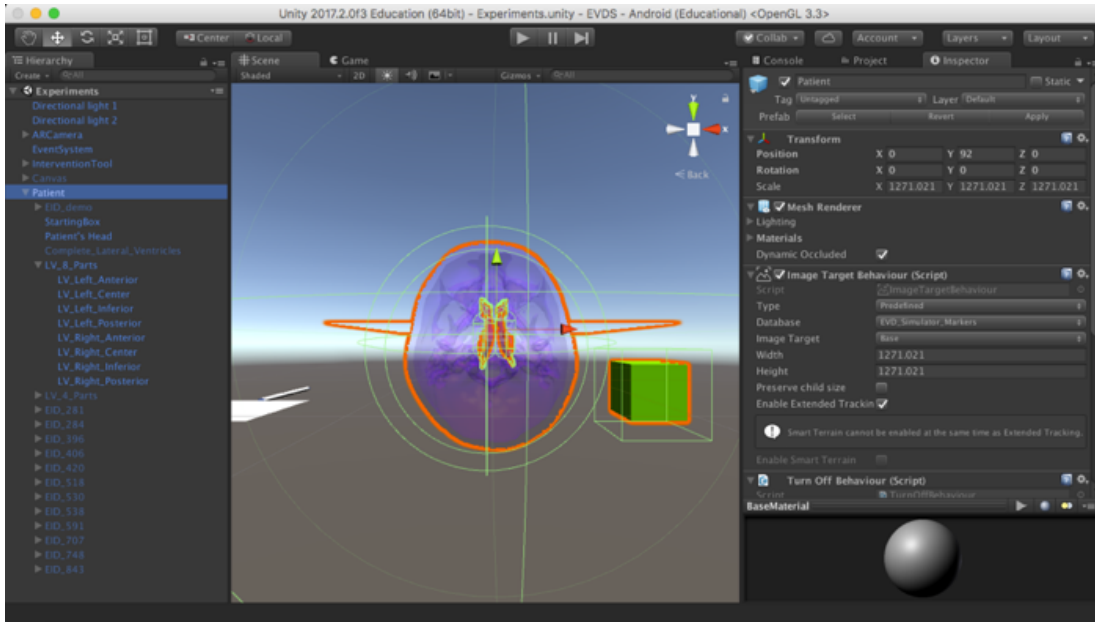
Fig. 4.4: Unity editor and PIM models.

specific visual representations (i.e., PSM) (Figure 4.2(3)). Then, we utilized the Unity

Player (i.e., code generator) in order to complete the virtual scene settings, a necessary

step to generate and deploy an artifact towards the desired platform (Figure 4.2(4)). Af-

terwards, the Unity Player converted the PSM and transformed it into the source code,

and deployed it towards a single platform based on the virtual scene settings through

command line programs (e.g., Shell).

We produced two executables for a stationary version (i.e. MacBook Pro machine)

and a portable version (i.e., Android LG Nexus 5 smartphone) with several prototypes

of each system to be validated by the domain expert in order to check how realistic they

are (Figure 4.2(4)). Lastly, we asked a novice to use both executables and to perform

the EVD placement tasks according to the neurosurgical scenario (Figure 4.2(5)).

4.3 Simulation modules description

4.3.1 Design considerations

We received well-defined requirements from the domain expert that include a few spec-ifications. The simulation modules need to build such that they will allow novices to apply the EVD placement task complying with an initial planning stage. The planning stage enables a series of surgical scenarios, including trial sets and entry points' position and rotation coordinates. The simulation modules need to allow for not only interaction with patient-specific 3D meshes but also for the performance of surface rendering with possible visual depth cues at running time. Moreover, the simulation modules would be deployed in stationary and portable environments to demonstrate extendibility with the potential for cross-platform deployment. During the trials, the simulation modules will record the novices' trajectory and time taken in the virtual space. The simulation modules also will offer a stereoscopic vision mode and record the novices' head and hand tracking (i.e. head and hand physical movements) prior to producing readable log files prior to users' performance analysis.

4.3.2 Simulation modules setup

Both generated executables needed two traceable and predefined fiducial markers, which are depicted at Figure 4.5. Flat markers (i.e., triangles) are consumed to render the 3D patient's head mesh, while multiple cube markers (i.e., multiple shapes) are consumed to render the 3D catheter's tube and tip meshes. The cube makers were mounted upon

cardboard papers and a wood stick for stability and mimicking the catheter's geometrical shape and weight.

Fig. 4.5: Physical version of the two trackable predefined fiducial markers.

The functionality of AR simulation modules depends on the integration of off-the-shelf software packages (i.e. Unity editor and libraries, and Vuforia). Unity is a sophisticated game engine that aims to create game scenes, and it allows for a mode to adjust 3D meshes-related configuration in terms of location, rotation, size, surface-based texture, and functionality within a game scene. Vuforia (Vuforia SDK version 5.5, Parametric Technology Corporation, Needham, Massachusetts, United States) is an image tracking and detection framework that provides device or objects detection and tracking functionality, stereo rendering, and reconstructing VR\AR scenes among the real-world space.

Many initial stages for AR systems, for instance, fiducial markers image processing, registration processing against the physical world, and camera calibration, are controlled through the integration between Unity and Vuforia. Vuforia empowers developers with a web service, Vuforia target manager, that receives and performs image processing of

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the fiducial markers. Vuforia target manager examines the validity of fiducial markers and ranks their tractability based on a local scale (i.e., augmentation level) by identifying image features and sharp edges. The more the fiducial markers are sharp with spiked features, carved texture, rich details, and good contrast, the higher will be the augmentation level, which increases the tracking robustness. Vuforia target manager is responsible to also to generate a trackable fiducial marker dataset (i.e. VuforiaDataset.unitypackage) as an input for the Unity Editor. Figure 4.6 indicates the fiducial markers after application of image processing and determining their detection landmark.
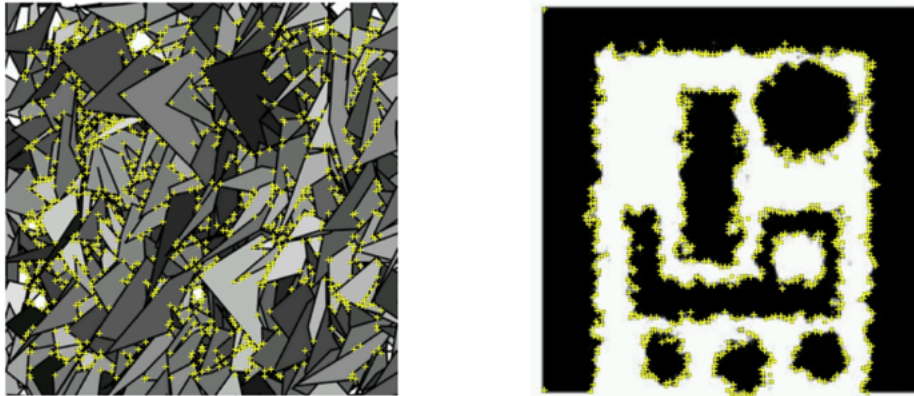
(a) The flat marker with registration points.   (b) The cube marker with registration points.

Fig. 4.6: The registration points in the soft version of the fiducial markers.

Whenever the trackable fiducial markers are integrated into the Unity editor, the Unity editor allows for a mode to maintain any 3D meshes aligned upon the physical version of fiducial markers in terms of location (X axis, Y axis, Z axis), rotation (rolls, pitch, yaw), and scale. The Unity Editor also offers a playing mode (i.e., testing mode) where the developers will be able to run the simulation scene and check the current registration settings for the whole 3D meshes with the game scene. It also allows for a pausing mode (i.e., debugging mode) to adjust the 3D meshes components of the AR

scene, if needed. Whenever any adjustments are performed or needed, the Unity Editor gives a visual feedback of the current state of these components, accordingly.

For camera calibration purposes, Vuforia SDK performs dynamic camera calibration by creating calibration profiles. The calibration profiles are created based on a model similar to the four-step internal camera model proposed by Heikkila and Silven [69]. The calibration profiles assumed that the intrinsic camera parameters are pre-calibrated, where it utilized the pre-defined markers in a real scene.

For the viewing mode, Unity and Vuforia integration allowed for a mode to select the simulation scene to be seen through mono or binocular views. Table 4.1 indicates the applied configurations to accomplish a stereoscopic view for the AR simulation modules:

Tab. 4.1: User viewing configuration applied to assign AR simulation scenes and functionality.

Attribute	Value
Eyewear type	Video see-through
Camera distortion mode	Dual texture for Android devices
Camera distortion coefficients	K1: 0.07. K2: 0.03
Field of view of the camera in degrees	95
Camera offset	0.09
Camera projection type	Orthographic
The clipping plane distance for the camera	Near: 0.05, Far: 5000
The viewing volume (depth) of an orthographic camera	700
Max simultaneous tracked objects\images	5
The aspect ratio (width divided by height).	Automatic
Frame per second	30 - 45

Figure 4.7 depicts the 3D meshes within the simulation modules scenes during
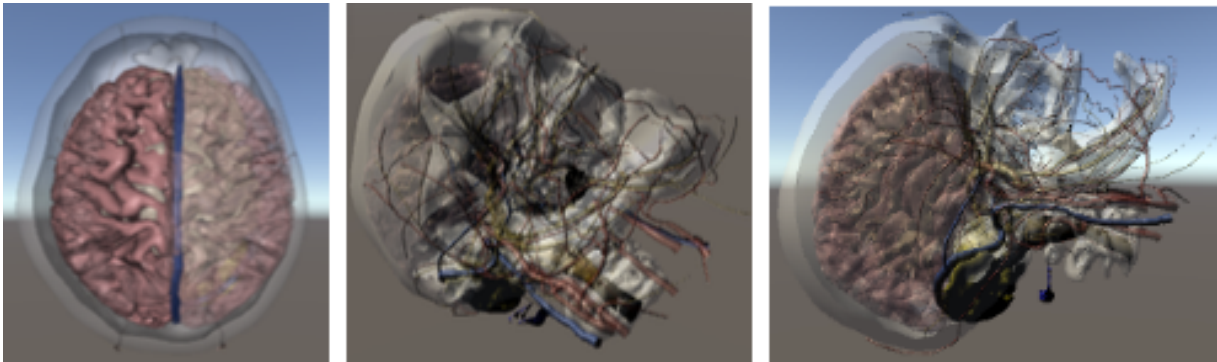
(a) Original skull meshes.
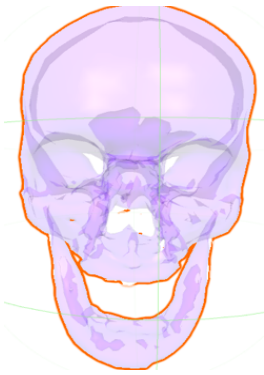
(b) The skull mesh in a transparent shedder.

(c) Ellipsoid (i.e. target).
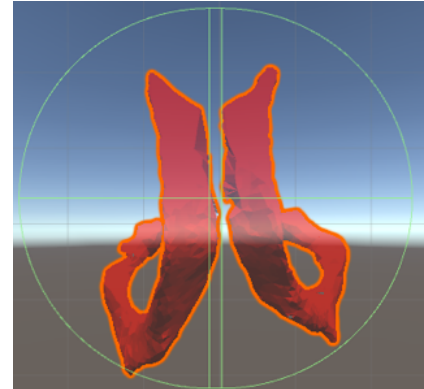
(d) Brain structures (Lateral ventricle).
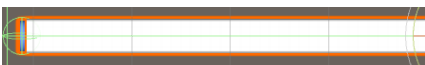
(e) Catheter and catheter's tip meshes.
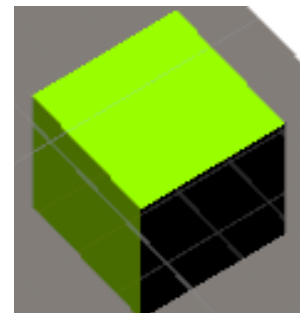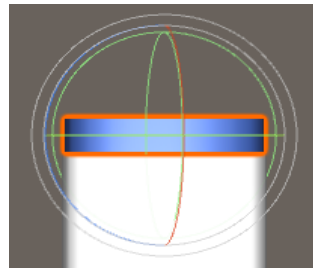
(f) Starting point.

**Fig. 4.7:** 3D meshes used with the AR simulation modules' scenes.

rendering mode. We integrated a set of 3D meshes into the Unity editor as the main assets of the game scene, where the Unity editor was used as a canvas to host the 3D meshes. The skull and brain structures meshes were designed through a sequential series of 362 high-resolution of a female patient. The images were converted into grayscale format prior to being inserted into Amira 5.6 (FEI Visualization Services Group, Hillsboro, OR) for manual segmentation purposes. The segmented objects (i.e., meshes) went through a multiple step process: 1) editing process of meshes through MeshLab (MeshLab 1.2.1., ISTI-CNR, Pisa, IT), and 2) refining process of missing surfaces or components though Blender 3D (Blender 3D 2.76, Blender Foundation, Amsterdam, Netherlands). More details about the meshes designing are available in [70]. Other meshes, for instance, ellipsoid, catheter, or catheter's tip, were designed from available geometrical shapes from the Unity library.

In each generated artifact, the AR simulation modules' screen includes two game scenes, which are depicted in Figure 4.8. The UI scene includes an eye chart image intended to allow users to adjust or calibrate the AR goggle's view with suitable distance according to their comfort. The AR scene includes a virtual camera, Vuforia dataset, 3D meshes (skull, brain structures, ellipsoids, catheter, catheter's tip, and the starting box). Other components were used, for instance, lights and audio sound effects, to give the AR simulation modules' scenes the best intuitive user experience.

For any EVD placement task, targets pose many challenges that require a particular eccentricity[2] while minimizing the cross-sectional area which emerged in clinical settings and has an impact upon the evaluation of users' performance. As a result, the choice

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2. It is the ratio of the longest axis to the shortest axis.
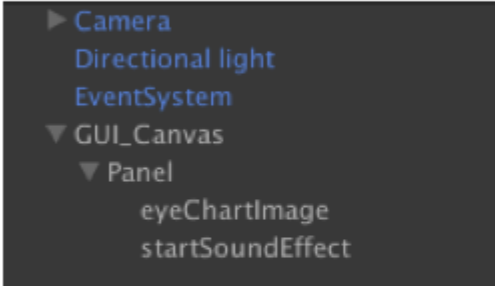
(a) The first game scene (i.e. UI) components of the AR simulation modules screen.
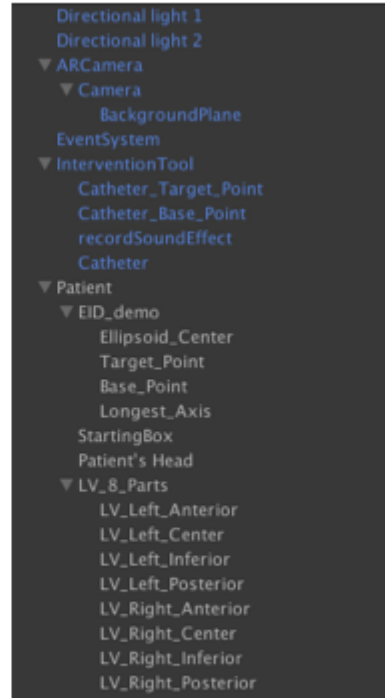
(b) The second game scene (i.e. AR scene) components of the AR simulation modules screen.

**Fig. 4.8:** The AR simulation modules' screen and underlying game scenes.

of geometry in the simulation modules for the EVD target has to comply with a similar shape with variable eccentricity. Ellipsoids are able to present enough eccentricity where the longest axis of the ellipsoid represents the ideal entry point for the task. Varying the ellipsoid's eccentricity, and ellipsoid's size, rotation, and scale increases the level of difficulty and complexity of the surgical sceneries. Thus, ellipsoids could be used to test users' targeting accuracy, spatial ability to identify the longest axis, and the needed dexterity to manipulate the EVD catheter's position and rotation prior to matching the target's longest axis. The more the EVD catheter's position and rotation match the ellipsoids target's longest axis, the more accurate the users' trajectory will be.

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4.3.3 Hardware description

A live demo of portable AR simulation module is available at https://youtu.be/
fDpfzJb9ixw. The first and the second generated artifact were deployed in the following environments, described in Table 4.2 and Figure 4.9. Both generated executables were deployed and running through a preliminary validation stage to ensure their usability for future assessment.

Tab. 4.2: Technical specifications of the used environments for the AR simulation modules.

Environment		Technical specifications
Stationery module	32″ screen	RCA TV, 1366x768 resolution, 16:9 widescreen.
	External camera	Logitech HD Webcam C270.
	MacBook Pro laptop machine	OS X El Capitan 10.11 operating system, 2.66 GHz Intel Core 2 Duo processor, and 16GB 1067MHz DDR3 Ram.
Portable module	AR goggle	Merge VR DSCVR headset with two 34 mm biconvex lenses, fits for 5.96″, screen phones, and purple color.
	LG Nexus 5 smart-phone	4.95″ screen, 1080x1920 resolution, 137.9x69.2x8.6 mm, Android v6.0 (Marshmallow) operating system, Quad-core 2.3 GHz Krait 400 processor, camera 8 MP.
Fiducial markers	Flat marker	Single image with multiple triangles shapes that uses Vuforia's Image target object.
	Cube marker	Four images with multiple shapes that use Vuforia's Image target object.
LED desk lamp		OttLite LED white lamp, 20.5″ height, different brightness settings (maximum of 345 lumens), and rubberized flexible neck.
Cardboard cube		Diameter x height $(7x7)$(cm).
Wood stick		Diameter x height $(0.5x24)$(cm).
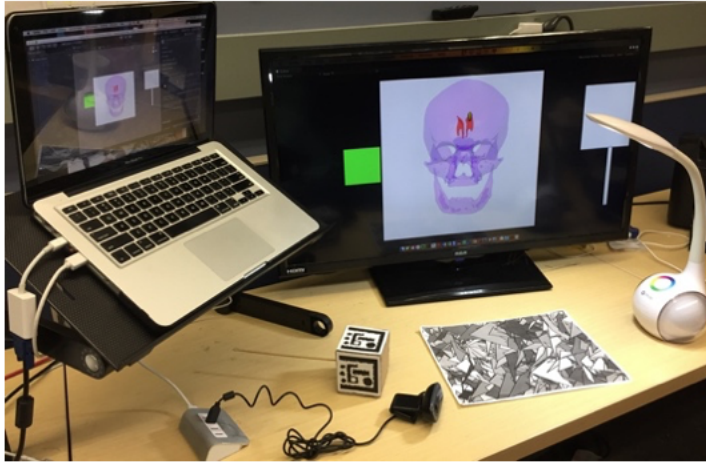
(a) The used environment for the first executable

(b) The used environment for the second executable.

Fig. 4.9: Overview of the generated executables and their environments.

4.3.4 Software description

The functionality of the AR simulation modules was written in C# programming language and Unity and Vuforia APIs. Unity and Vuforia are proprietary software; hence, much of their source code is not accessible. The integration between Unity and Vuforia APIs allowed maintaining many of the current simulation features, for instance, surface rendering, GUI interaction, collision detection, feedback graphics rendering, and dynamic perspective tracking.

We followed a rapid prototyping development process to create several prototypes to be reviewed by the domain expert. Whatever feedback we received from the domain expert, we employed in the next development spiral. Figure 4.10 and Figure 4.11 depicts the use case diagram and the class diagram for the AR simulation modules, respectively.
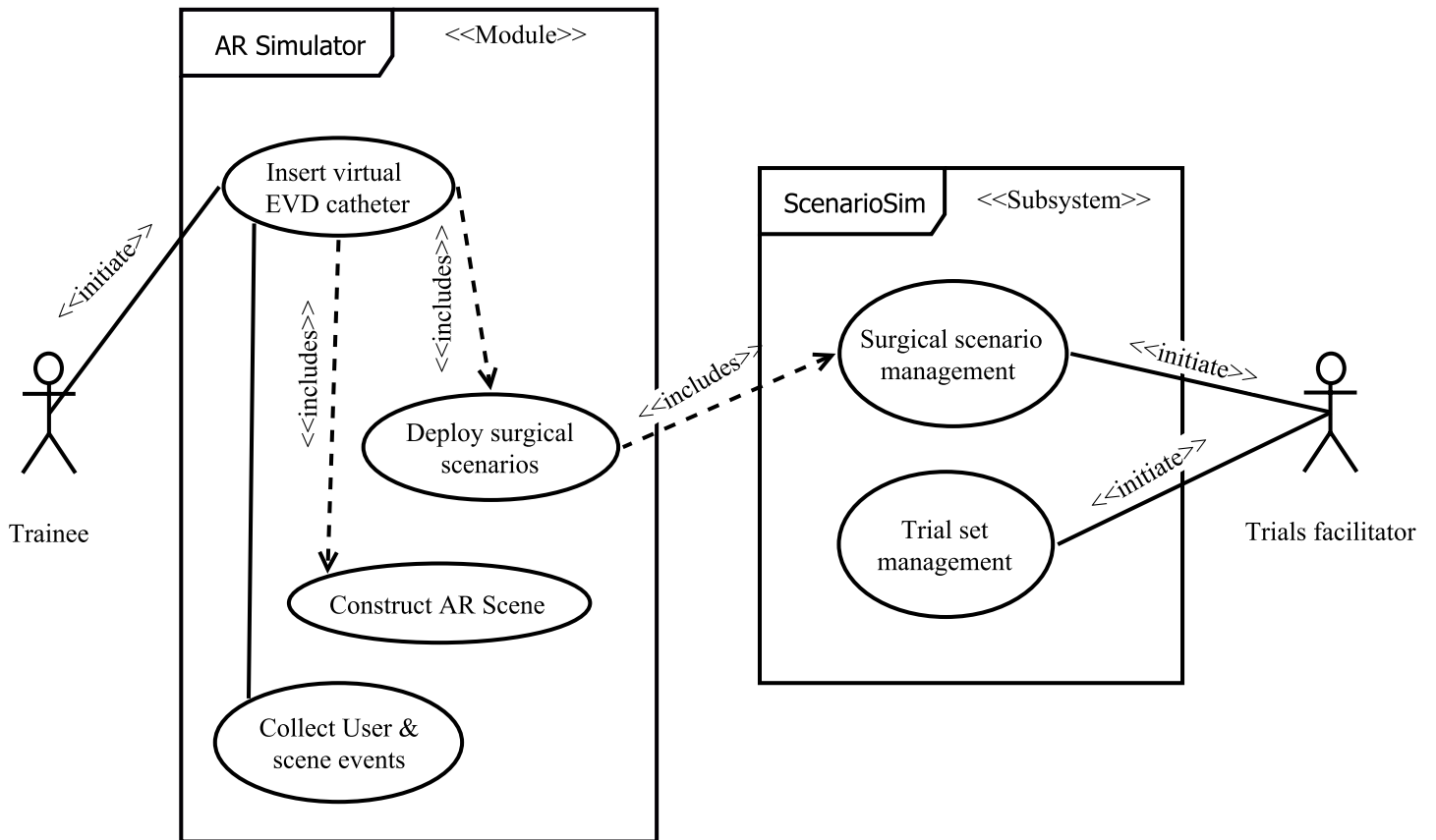
Fig. 4.10: Use case diagram for the AR simulation modules.
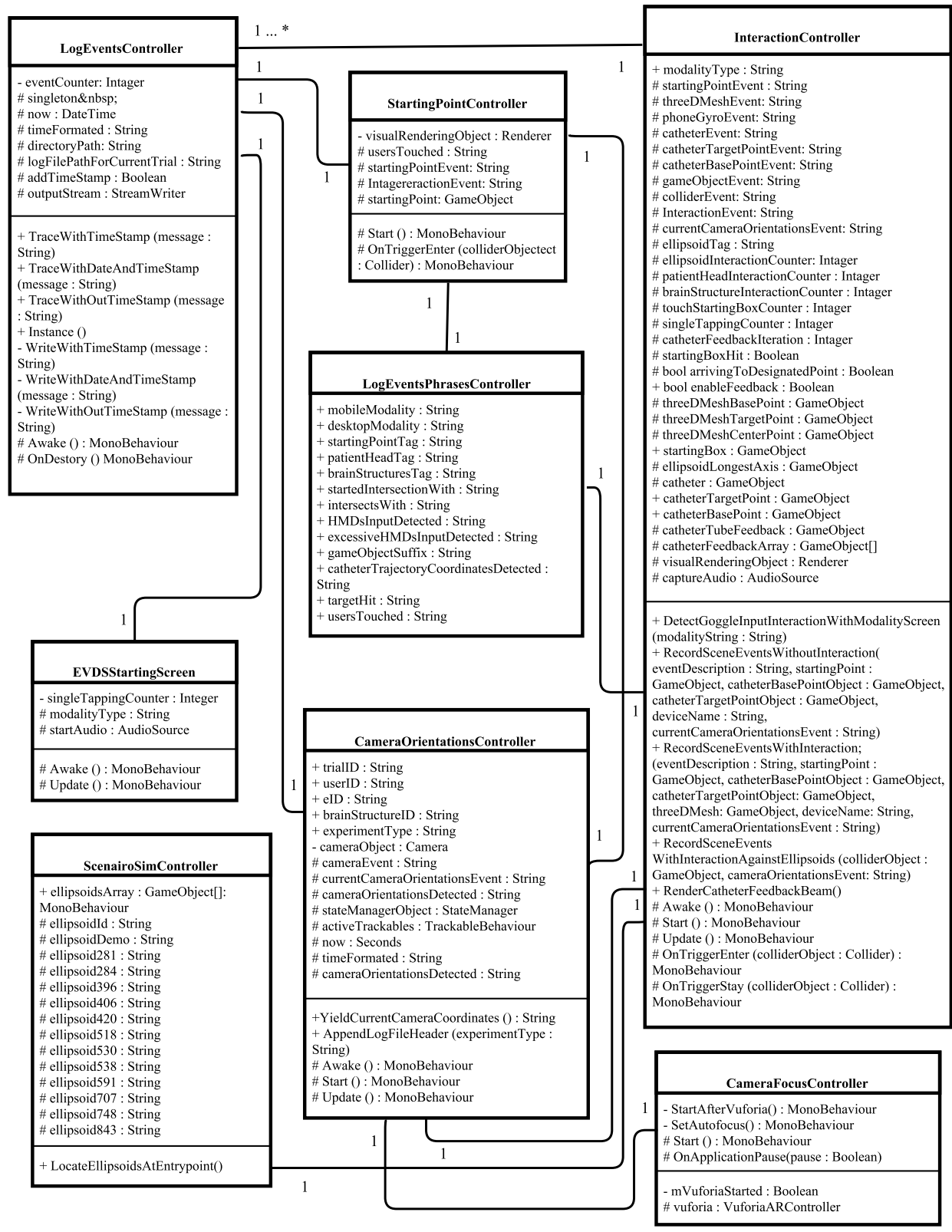
Fig. 4.11: Class diagram for the AR simulation modules.

4.3.5 Architecture

Figure 4.13 presents an overview of the used architecture to deploy the generated executables.
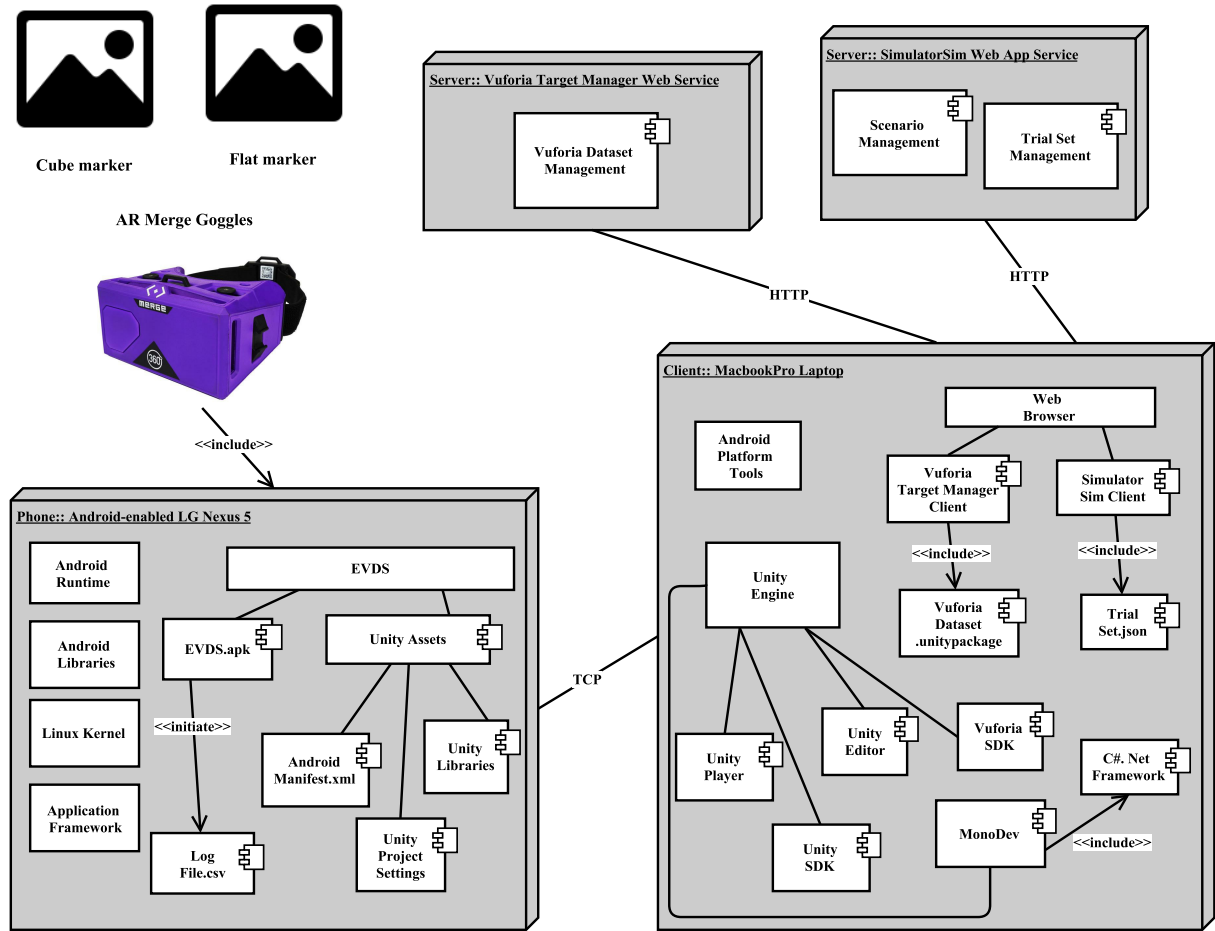
Fig. 4.12: Deployment diagram of the AR simulation modules' architecture.

4.3.6 User performance evaluation

Users' performance evaluation is a key aspect of the validity of any solution in the context of surgical simulations. The evaluation of novices' performance usually focuses on

quantifying their surgical competency through the speed and accuracy metrics of psychomotor tasks. Since any surgical task involves a psychomotor task in single or multiple degrees of freedom, the assessment of novices' performance should involve a 3D extension of Paul Fitts methodology or Fitts' Law [51] (refer to Section 2.7.3). Fitts' Law allows the determination and prediction of human movement as a trade-off between their accuracy and speed during a single degree-of-freedom (DOF) task. Figure 4.13 presents an example of the criterion of how users' performance evaluation will be interpreted. In the beginning of the trials, novices would fall into the Fast-Not-So-Accurate zone with being fast task performers (high speed, low accuracy). Then, novices would fall in the Slow-Not-Accurate zone with being slow and almost-zero accuracy (low speed, low accuracy). Both the former and the latter zones would include novices with low spatial abilities. Also, novices would fall into the Very-Fast-Very-Accurate zone that being in the state of optimal performance (high speed, high accuracy), which is very rare. Finally, novices would fall into the Very-Slow-Very-Accurate zone whenever they improved and had better targeting and visual-spatial abilities (low speed, high accuracy). Whenever novices' performance trend come closer to the Very-Slow-Very-Accurate zone, this is an indication of their performance improvement.

Once the user begins to perform an EVD placement task, the AR simulation modules will provide a mode of evaluation by collecting users' events, for instance, tracking of users' path and trajectory, catheter movement, viewpoint, and time. As soon as a number of the trials set have been completed, the events of the users' trials will be clustered and consumed through the third party component (i.e., SimulatorSim) as a log file, represented in Comma Separated Values (CSV). An example of an EVD placement trial
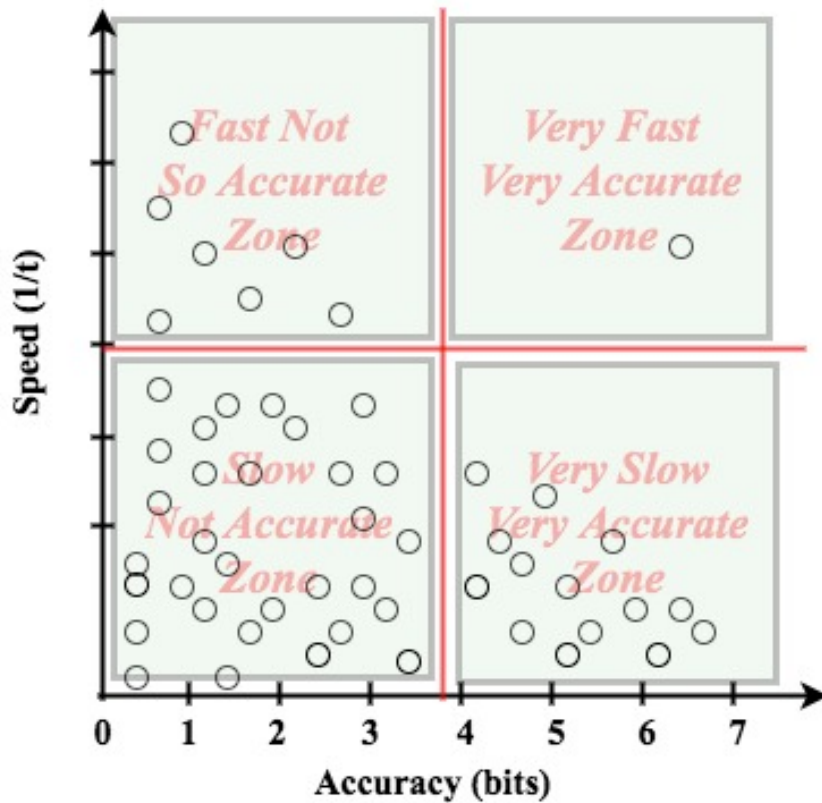
Fig. 4.13: Example of users' speed and accuracy trade-off diagram and its implications on their performance.

output is depicted in Figure 4.14.

Each log file contains the users' path\trajectory events from the starting point until completing the trial. The log file includes time stamps, users' event description (e.g. users' viewpoint events, starting or ending of the trial, catheter's colliding with ellipsoids), and the position axis vector (X,Y,Z) and rotation quaternion (W,X,Y,Z) of different 3D meshes.

counter	Time (hh:mm:ss.mmm)	Event Description	StartingPointPosition			CatheterTipPosition			CatheterTipRotation				CatheterRotation				HeadRotation			
	2017/Oct/02	Loging_started	X	Y	Z	X	Y	Z	W	X	Y	Z	W	X	Y	Z	W	X	Y	Z
449	12:26:59.065	HMDs input detected				1949.00	-281.00	511.57	-0.06	0.06	0.70	-0.70	-0.06	0.06	0.70	-0.70	0.00	0.03	-0.45	-0.89
684	12:27:02.270	Catheter trajectory coordinates detected				573.77	-76.95	-165.01	-0.05	0.60	-0.46	0.65	-0.05	0.60	-0.46	0.65	-0.02	0.09	-0.46	-0.88
687	12:27:02.309	Catheter trajectory coordinates detected				585.42	-95.54	-162.02	-0.05	0.60	-0.46	0.66	-0.05	0.60	-0.46	0.66	-0.02	0.09	-0.46	-0.88
688	12:27:02.309	Catheter trajectory coordinates detected				585.42	-95.54	-162.02	-0.05	0.60	-0.46	0.66	-0.05	0.60	-0.46	0.66	-0.02	0.09	-0.46	-0.88
689	12:27:02.351	The user touched the starting point	789.30	-313.94	0												-0.02	0.09	-0.46	-0.88
692	12:27:02.372	Catheter trajectory coordinates detected	789.30	-313.94	0	601.65	-113.99	-158.48	-0.06	0.60	-0.45	0.66	-0.06	0.60	-0.45	0.66	-0.02	0.10	-0.46	-0.88
693	12:27:02.373	Catheter trajectory coordinates detected	789.30	-313.94	0	601.65	-113.99	-158.48	-0.06	0.60	-0.45	0.66	-0.06	0.60	-0.45	0.66	-0.02	0.10	-0.46	-0.88
983	12:27:06.162	Catheter trajectory coordinates detected	789.30	-313.94	0	53.99	226.59	-627.64	-0.04	0.66	-0.46	0.59	-0.04	0.66	-0.46	0.59	-0.01	0.05	-0.49	-0.87
984	12:27:06.192	Catheter intersects with Patient's Head	789.30	-313.94	0	53.99	226.59	-627.64	-0.04	0.66	-0.46	0.59	-0.04	0.66	-0.46	0.59	-0.01	0.05	-0.49	-0.87
989	12:27:06.248	Catheter intersects with Patient's Head	789.30	-313.94	0	47.11	230.69	-623.82	-0.05	0.66	-0.46	0.59	-0.05	0.66	-0.46	0.59	-0.01	0.05	-0.49	-0.87
990	12:27:06.250	Catheter intersects with Patient's Head	789.30	-313.94	0	47.11	230.69	-623.82	-0.05	0.66	-0.46	0.59	-0.05	0.66	-0.46	0.59	-0.01	0.05	-0.49	-0.87
1075	12:27:06.829	Catheter started intersection with Lateral_Ventricles	789.30	-313.94	0	22.66	215.18	-532.37	-0.09	0.67	-0.47	0.56	-0.09	0.67	-0.47	0.56	-0.01	0.05	-0.49	-0.87
1076	12:27:06.830	Catheter intersects with Lateral_Ventricles	789.30	-313.94	0	22.66	215.18	-532.37	-0.09	0.67	-0.47	0.56	-0.09	0.67	-0.47	0.56	-0.01	0.05	-0.49	-0.87
1238	12:27:07.725	Catheter trajectory coordinates detected	789.30	-313.94	0	44.20	14.78	-414.64	-0.11	0.68	-0.45	0.57	-0.11	0.68	-0.45	0.57	-0.01	0.05	-0.49	-0.87
1239	12:27:07.726	Catheter trajectory coordinates detected	789.30	-313.94	0	44.20	14.78	-414.64	-0.11	0.68	-0.45	0.57	-0.11	0.68	-0.45	0.57	-0.01	0.05	-0.49	-0.87
1240	12:27:07.757	Catheter started intersection with Ellipsoid	789.30	-313.94	0	44.20	14.78	-414.64	-0.11	0.68	-0.45	0.57	-0.11	0.68	-0.45	0.57	-0.01	0.05	-0.49	-0.87

Fig. 4.14: Example of EVD placement log file generated after the users' trial being completed.

4.4 Discussion

We believe the simplicity of our design is a valuable contribution that makes such designs more available to a wider range of users. The generated executables allowed users not only to perform the EVD placement tasks through an intuitive user interface but also allowed users to be exposed to many aspects of the AR simulation scene with minimum mental transformations between different coordinate systems. The generated executables also followed plug-and-play concepts in terms of installing and running the executables. In addition, the generated executables take small or almost-no space at the working space, and they offer a similar experience to the previous systems within the clinical settings. They also allow users to move laterally around the virtual scene, providing micro and macro views of the workspace. Moreover, the generated executables allowed for a mode of feedback and evaluation; therefore, they will be transparent to the users in terms of errors or loss of tracking.

With the proposed development approach, given the starting state of the scenario, an evaluator of the users' performance can reconstruct the state of the surgical task

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performance at any point within the performance; this reconstruction allows the evaluator to replay the performance and analyze the performance in a very robust manner.

For any EVD placement tasks, EVD targets pose many challenges, for instance, a particular eccentricity (i.e. ratio of the longest to the shortest axis) with minimizing the cross-sectional area, emerged in clinical settings in terms of evaluation of users' performance. Therefore, the choice of geometry in the AR simulation module has to comply with similar geometrical restrictions. Ellipsoid, the best candidate, could be used to test users targeting accuracy, spatial ability to identify the longest axis and to manipulate the EVD catheter's position and rotation. We believe ellipsoids are suitable targets for EVD targeting tasks because ellipsoids offer unique targeting trajectory through its longest-axis, ellipsoids allow the easy-rendering process, and human should not consume much of their cognitive abilities to target them. In addition, varying the ellipsoids eccentricity, and ellipsoids size, rotation, and scale increases the level of difficulty and complexity of the surgical scenarios.

Although MDE provides many advantages for quality software development, rapid prototypes for research improvement, and consistent professional feedback, MDE is still in an immature stage, and it suffers from many challenges. For example, MDE has been seen as a long-term investment, where the domain experts and experienced developers need to maintain best practices in terms of implementation and testing approaches. The standardization of the best practices for a particular domain typically consumes a long time, a major concern in rapid-deliverables-driven software cultures. However, whenever the best practices for a particular domain are set, other important costs will be minimized, for instance, maintenance, consultation, or automation costs, in the long

term, accordingly.

One limitation of this work is that the current used surgical scenario depends on a single patient dateset with normal brain structures, and there is a need for a variety of imaging studies including slim, shifting, narrow, or abnormal brain structures.

Although the integration of the Unity and the Vuforia is a wise chain of tools to implement into AR applications, we noticed in the preliminary testing that users struggle with loss tracking of 3D brain structures meshes in the AR scene due to light discrepancies. Using the LED lamp as the main lighting source with the room's lightings improved tracking compared to without the LED lamp. Other concerns we noticed were that users might lose track of the 3D catheter's tool mesh while performing the targeting task due to the 3D catheter mesh being outside the boundaries of the AR goggle's field of view (FOV). We were able to handle this concern by using four images of the same cube marker, where the rendering of the 3D catheter's tool mesh would be active more frequently whenever the user moved the cube marker.

Another concern from users was about depth perception, a common problem in AR systems. This phenomenon becomes obvious the more the users wanted to physically move the fiducial markers to gain a better view of the position and rotation of ellipsoid's longest axis. Depth perception has been considered a challenge due to the fact that humans tend to perceive depth motion of an object as primary a perceptual experience as the perception of its static flatness [71]. This phenomenon led to many challenges when designing 3D graphical user interfaces (GUIs), for instance, distance underestimation [72]. Such phenomena need further investigation.

4.5 Summary and Conclusions

In this chapter, we described our efforts to develop two proof-of-concept AR simulation modules for the training and planning aid of an EVD placement task. Our contribution in this chapter is that this work should be seen as a detailed MDE case study for the development of AR surgical task-oriented training and planning aid simulation modules. The next stage of this research is to examine our executables for verification purposes to measure the performance of novice users during their EVD targeting tasks within different surgical scenarios and trials.

Chapter 5

AR Training and Planning Simulation Modules for EVD Placement Tasks As Assessment Tools

5.1 Introduction

The second aim of our research is demonstrating the feasibility of the developed AR simulation modules to detect quantitative differences in performance between novices with different knowledge backgrounds in two settings. This chapter describes two separate but related experimental designs: the first study (User Study 01), and the second study (User Study 02). The first study objectively measured users' performance during

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- This work has been published as:

  - H. Ghandorh, S. De Ribaupierre, R. Eagleson, "Neurosurgery Planning and Training for Targeting Tasks in Augmented Reality Environment: User Performance Analysis," Poster, London Health Research Day 2017, March 2017, London, Ont, Canada.

targeting tasks into virtual ellipsoids meshes, while the second study objectively measured users' performance while carrying out targeting tasks into virtual brain structures meshes.

Both studies used the same apparatus, targeting task procedures, and evaluation methodology. Subjects' performance in the studies were calculated based on Fitts' Law (refer to Section 2.7.3), as a trade-off between speed and accuracy.

Both studies were conducted within two sessions. The subjects at the first session (first setting[1]) of the studies were performing the targeting tasks, as part of an investigation into their hit rate. Hit rate refers to the extent to which a subject arrives at the designated target in the virtual world. The subjects in the second session (second setting) of the studies were performing the targeting tasks, as part of an investigation into improving their depth estimation with head motion and perceptual motion cues. In the first setting, the subjects performed EVD targeting tasks with only hand motions, while they performed EVD targeting tasks with hand and head motion in the second setting.

As soon as the subjects finish a trial, the AR simulation module will collect performance metrics that include hit rate, ID, MT, IP, distance between the virtual catheter's tip and the center of the target (Distance Error (DE)), distance between the virtual catheter's tube and the ellipsoid's longest axis (Transitional Error (TE)), angle difference between the virtual catheter's tube and the ellipsoid's longest axis (Rotational Error (RE)), and difference between the subjects' original head angle and the subjects' last head angle during hitting the targets (Head Rotation of Time) (HRt). ID, MT, IP, and

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1. Setting term means the state in which a subject performs the targeting task.

DE were collected during the first and second settings in each study, while the *HRt* was only collected through the second setting in each study. *TE* and *RE* were only collected in the User Study 01.

5.2   User Study 01

5.2.1   Subjects

Table 5.1 presents some information about the subjects in this study. 12 novice undergraduate\graduate students participated in this study. The subjects came from two backgrounds: medical, and software engineering. The subjects were 64% female, and more than 90 % of subjects had no anatomical or simulation backgrounds. User12 did not follow the proposed procedure, therefore we excluded the subject's results from the study.

Tab. 5.1: Subjects demographics in the User Study 01.

User ID	Age	Gender	Background
User01	20 - 29	Female	Medical
User02	20 - 29	Male	Computer Engineering
User03	20 - 29	Female	Biomedical Engineering
User04	20 - 29	Female	Computer Engineering
User05	30 - 39	Female	Computer Engineering
User06	20 - 29	Female	Computer Science
User07	20 - 29	Male	Computer Engineering
User08	20 - 29	Female	Computer Science
User09	20 - 29	Male	Computer Engineering
User10	20 - 29	Female	Biomedical Engineering
User11	30 - 39	Male	Computer Engineering

All subjects were given basic instructions regarding the tasks, and they had access to the AR simulation modules for demonstration purposes prior to the beginning of the study. Due to the fact that the majority of subjects did not have a surgical background, their targeting tasks were entirely visuospatial in nature and anatomical knowledge was not a priority in this study.

5.2.2 Apparatus/Materials

In this study, the portable version of the AR simulation module was used (refer to Section 4.3). There were 12 virtual ellipsoids, as targets, with a variety of positions and orientations within predefined targeting area.

5.2.3 Procedure

Each subject completed 12 targeting tasks into 12 different virtual ellipsoids in the first setting and 12 targeting tasks into the 12 different virtual ellipsoids in the second setting, resulting in 264 trials. Each subject performed the targeting tasks through a designated set of trials within 30 minutes, in a single meeting. The designated set of trials were generated based on a balanced Latin square table, built based on the upper and lower geometrical boundaries (i.e., position, rotation, and size) of each target.

Figure 5.1 presents a workflow of the EVD placement task within the AR simulation module in the first setting. Any user follows the same flow where he and she needs to wear the AR goggle headset with the smartphone mounted in, project the AR goggle towards the fiducial markers, navigate towards the starting point (i.e., 3D green box

mesh), navigate to the rendered ellipsoid, and accurately hit the ellipsoid's longest axis. During the targeting journey, the user needs to press any of the AR goggle's dual inputs to record an event about switching screens (changing from the UI scene to the AR scene), starting the trial (before navigating to the starting point), and ending the trial (after arriving at the ellipsoid).

Figure 5.2 and Figure 5.3 show a subject performs the EVD placement task and his or her view during a trial, respectively. Each task involved planning, targeting, and feedback. In the planning stage, the subject used the AR simulation module to view the rendered ellipsoid. Following the planning stage, targeting tasks involved placing the virtual EVD catheter's tip into the center of the ellipsoid, making a trajectory comply with the longest axis of the ellipsoid. Finally, visual feedback was given after each task, where two virtual beams rendered, one for the subject's trajectory and the other beam for the longest axis of the ellipsoid. The visual feedback intended to notify the subjects about their current trajectory, as part of their learning process and building a mental view of better targeting practices. In order to ensure better learning, subjects targeted the ellipsoids, designed with different location and angle by which leading to different ellipsoids with different feedback.
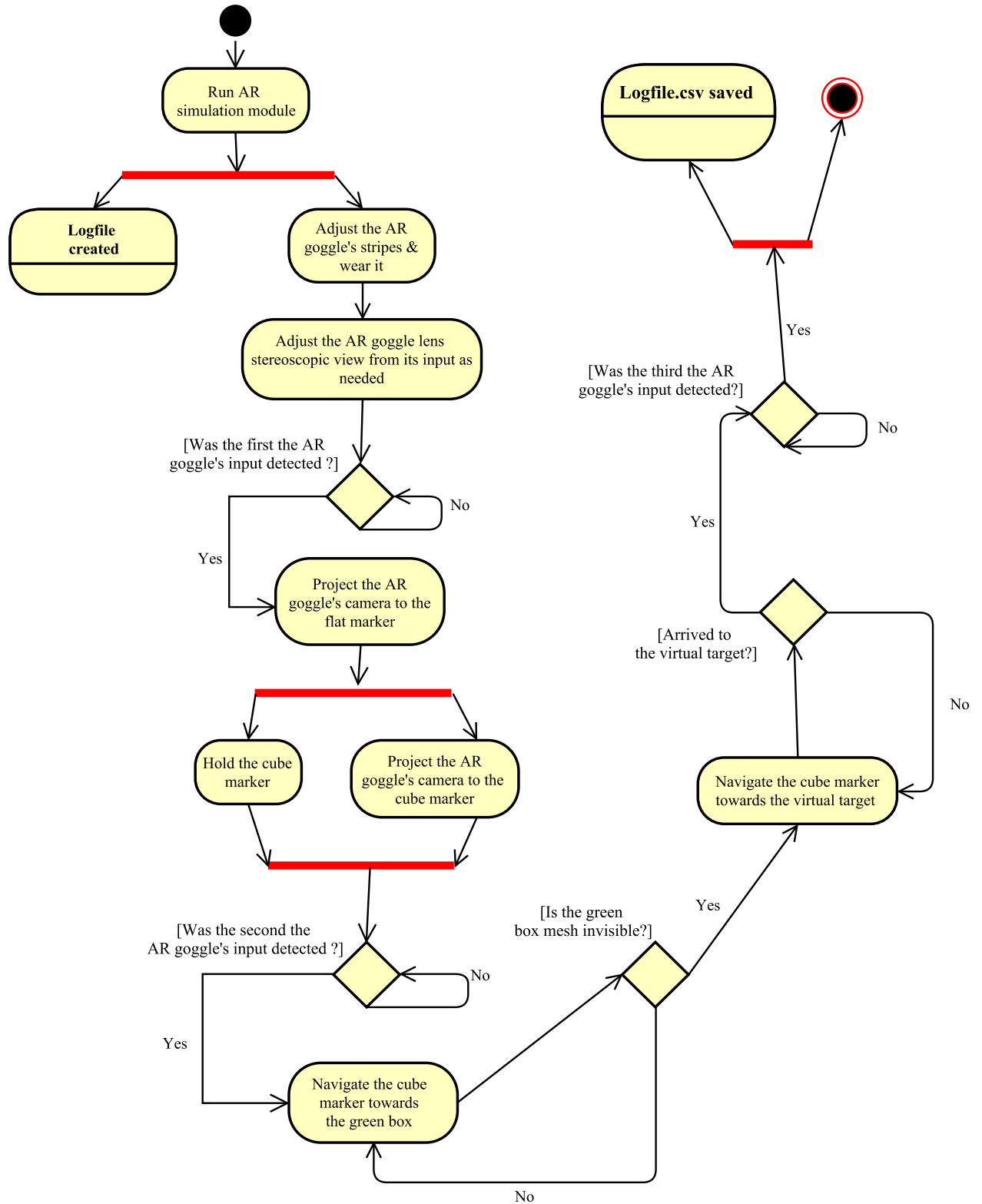
Fig. 5.1: Workflow of EVD placement targeting tasks using the AR simulation module in the first setting. Users will move only their hands.

Fig. 5.2: Example of a trial on the AR simulation module.
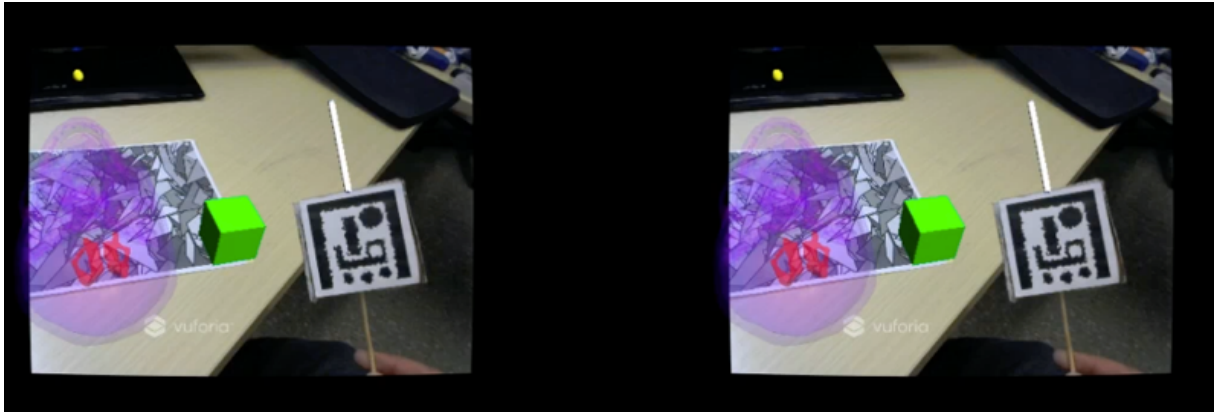
(a) Rendering the complete AR simulation scene and the starting of a trial.
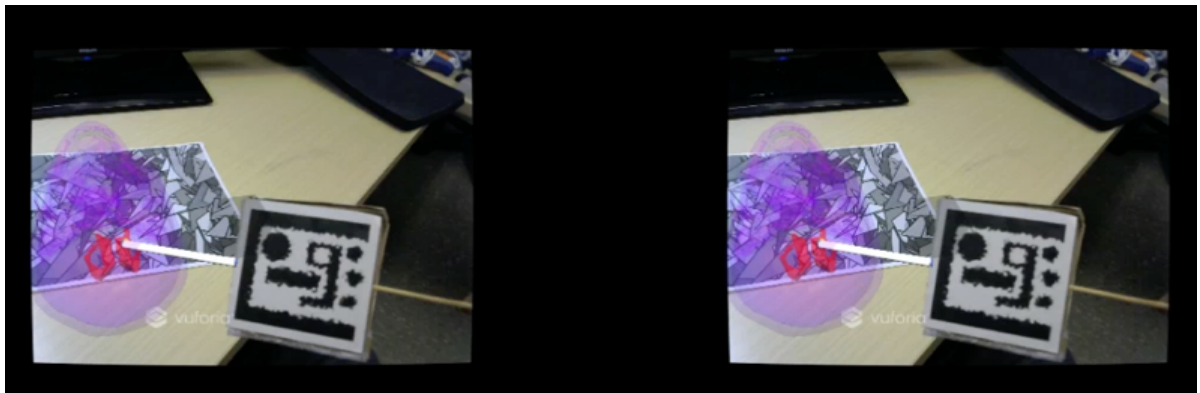
(b) The subject arrived at the ellipsoid and completing the trial.

(c) Visual feedback appeared for ellipsoid's longest axis (cyan beam) and the subject's trajectory (blue beam)

Fig. 5.3: The subject's stereoscopic view through the running of trial.

5.2.4 Results

Table 5.2 and Table 5.3 depict the outcome of the subjects' trials in terms of the tasks description, and the subjects' hit rate through the first and second settings, respectively. Overall, the data showed that the subjects were able to achieve the majority of the tasks with 100% hit rate. 54% of the subjects spent more time (i.e., more accuracy) in the second setting than the first setting, while 36% spent less time (i.e., less accuracy) in the second setting than the first setting.

Tab. 5.2: Mean and stand deviation values of subjects' tasks and its description throughout the User Study 01 in the first setting.

User ID	Trial counter	A (cm)	W (cm)	ID (bits)	MT (seconds)	IP (bits/ seconds)	Hit rate (%)
User01	12	7.8 ± 3.7	0.3 ± 0	4.2 ± 2	8.4 ± 6.2	0.53 ± 0.43	83
User02	12	9.4 ± 0.43	0.3 ± 0	5 ± 0.066	20 ± 11	0.32 ± 0.16	100
User03	12	9.4 ± 0.43	0.3 ± 0	5 ± 0.066	11 ± 6.2	0.58 ± 0.32	100
User04	12	9.4 ± 0.43	0.3 ± 0	5 ± 0.066	19 ± 15	0.37 ± 0.2	100
User05	12	9.4 ± 0.43	0.3 ± 0	5 ± 0.066	13 ± 11	0.69 ± 0.5	100
User06	12	9.4 ± 0.43	0.3 ± 0	5 ± 0.066	11 ± 9.2	0.75 ± 0.5	100
User07	12	9.4 ± 0.43	0.3 ± 0	5 ± 0.066	18 ± 4.8	0.3 ± 0.093	100
User08	12	9.4 ± 0.43	0.3 ± 0	5 ± 0.066	27 ± 29	0.36 ± 0.29	100
User09	12	9.4 ± 0.43	0.3 ± 0	5 ± 0.066	16 ± 13	0.52 ± 0.32	100
User10	12	9.4 ± 0.43	0.3 ± 0	5 ± 0.066	15 ± 15	0.52 ± 0.25	100
User11	12	9.4 ± 0.43	0.3 ± 0	5 ± 0.066	21 ± 16	0.49 ± 0.58	100

Tab. 5.3: Mean and stand deviation values of subjects' tasks and its description throughout the User Study 01 in the second setting.

User ID	Trial counter	A (cm)	W (cm)	ID (bits)	MT (seconds)	IP (bits/ seconds)	Hit rate (%)
User01	12	9.4 ± 0.43	0.3 ± 0	5 ± 0.066	15 ± 7.7	0.48 ± 0.32	100
User02	12	9.4 ± 0.43	0.3 ± 0	5 ± 0.066	14 ± 7.3	0.49 ± 0.32	100
User03	12	9.4 ± 0.43	0.3 ± 0	5 ± 0.066	14 ± 4.3	0.38 ± 0.11	100
User04	12	9.4 ± 0.43	0.3 ± 0	5 ± 0.066	13 ± 4.5	0.45 ± 0.19	100
User05	12	9.4 ± 0.43	0.3 ± 0	5 ± 0.066	13 ± 8.1	0.52 ± 0.25	100
User06	12	9.4 ± 0.43	0.3 ± 0	5 ± 0.066	18 ± 20	0.47 ± 0.28	100
User07	12	9.4 ± 0.43	0.3 ± 0	5 ± 0.066	26 ± 12	0.24 ± 0.13	100
User08	12	9.4 ± 0.43	0.3 ± 0	5 ± 0.066	15 ± 5.2	0.37 ± 0.11	100
User09	12	9.4 ± 0.43	0.3 ± 0	5 ± 0.066	14 ± 8	0.52 ± 0.33	100
User10	12	9.4 ± 0.43	0.3 ± 0	5 ± 0.066	23 ± 32	0.39 ± 0.2	100
User11	12	9.4 ± 0.43	0.3 ± 0	5 ± 0.066	30 ± 20	0.33 ± 0.39	100

Table 5.4 and Table 5.5 depict the subjects' metrics including DE, TE, and RE through the first setting and the second settings, respectively. Overall, the data showed that 27% of the subjects had an improvement in their DE metric values as a comparison between the first setting and the second setting. Additionally, 27% of the subjects had an improvement in their RE metric values, while 36% of the subjects did not show any improvement. However, 81% of the subjects had improved in their TE metric values between the first setting and the second setting.

Tab. 5.4: Mean and stand deviation values of subjects' *DE*, *TE*, and *RE* throughout the User Study 01 in the first setting.

UserID	*DE* (cm)	*TE* (cm)	*RE* (cm)
User01	0.41 ± 0.2	1.8 ± 1.3	1.2 ± 0.65
User02	0.5 ± 0.098	1 ± 0.28	1.5 ± 0.32
User03	0.54 ± 0.033	0.83 ± 0.45	1.6 ± 0.22
User04	0.5 ± 0.046	1.7 ± 0.83	1.4 ± 0.28
User05	0.52 ± 0.043	2 ± 1.3	1.1 ± 0.41
User06	0.43 ± 0.095	2.5 ± 0.82	1.3 ± 0.3
User07	0.52 ± 0.053	5 ± 1.3	1.5 ± 0.12
User08	0.5 ± 0.045	2.5 ± 1.3	1.2 ± 0.45
User09	0.46 ± 0.094	3 ± 0.84	1.4 ± 0.17
User10	0.42 ± 0.11	1.3 ± 0.6	1.3 ± 0.23
User11	0.48 ± 0.074	1.5 ± 1.5	1.4 ± 0.38

Tab. 5.5: Mean and stand deviation values of subjects' *DE*, *TE*, and *RE* throughout the User Study 01 in the second setting.

UserID	*DE* (cm)	*TE* (cm)	*RE* (cm)
User01	0.47 ± 0.10	2.50 ± 1.1	1.30 ± 0.25
User02	0.48 ± 0.09	1.10 ± 0.4	1.50 ± 0.30
User03	0.53 ± 0.02	0.67 ± 0.4	1.50 ± 0.30
User04	0.52 ± 0.04	1.50 ± 0.6	1.30 ± 0.29
User05	0.49 ± 0.09	1.30 ± 1.5	1.10 ± 0.39
User06	0.48 ± 0.09	2.10 ± 0.9	1.40 ± 0.34
User07	0.50 ± 0.07	4.80 ± 2.0	1.60 ± 0.11
User08	0.53 ± 0.05	1.40 ± 0.9	1.20 ± 0.43
User09	0.50 ± 0.04	1.80 ± 1.3	1.40 ± 0.38
User10	0.51 ± 0.05	1.00 ± 0.6	1.40 ± 0.27
User11	0.53 ± 0.03	1.50 ± 1.5	1.30 ± 0.36

5.3   User study 02

5.3.1   Subjects

In this study, 13 novice undergraduate\graduate students and one senior neurosurgeon participated in this study. The subjects came from two backgrounds: anatomy, and medicine. The subjects were 60% female, and 60% of the subjects had access to anatomical courses or materials. Table 5.6 presents some information about the subjects in this study. The results of three subjects (User06, User09, User11) were excluded due to not completing the study or they had eye health-related problems.

Tab. 5.6: Subjects demographics in the User Study 02.

User ID	Age	Gender	Expertise Level	Background
User01	20-29	Female	Novice	Medical
User02	20-29	Male	Novice	Anatomy
User03	20-29	Male	Novice	Anatomy
User04	20-29	Male	Novice	Anatomy
User05	20-29	Female	Novice	Anatomy
User07	20 - 29	Female	Novice	Anatomy
User08	20 - 29	Female	Novice	Medical
User10	20 - 29	Male	Novice	Anatomy
User12	20 - 29	Female	Novice	Medical
Senior User01	40 - 50	Female	Senior Neurosurgeon	Medical

All subjects were given basic instructions regarding the tasks, and they had access to the AR simulation modules for demonstration purposes prior to the beginning of the study.

5.3.2   Apparatus/Materials

In this study, the portable version of the AR simulation modules was used. The targets included eight parts of the lateral ventricle meshes: left inferior, right Inferior, left body, left posterior, right body, right posterior, left anterior, and right anterior horns of the brain.

5.3.3   Procedure

Each subject completed 8 targeting tasks into the eight virtual brain structures in the first setting, and 8 targeting tasks into the virtual brain structures in the second setting (i.e., total trials is 160). Each subject performed the targeting tasks through a designated set of trials within 30 minutes and in a single session. The designated set of trials were generated based on a balanced Latin square table.

Figure 5.4 presents a targeting task procedure that subjects will follow to complete their trials in the second setting.

Each task involved planning, targeting, and feedback. In the planning stage, the subject used the AR simulation module to view the virtual brain structures. Following the planning stage, targeting tasks involved placing the virtual EVD catheter's tip into the center of the brain structures. No visual feedback was given after each task. The targeting tasks on this study conducted as a mean for basic understanding used to determine a hit rate, but this required some level of visuospatial abilities. Therefore, the subjects needed to demonstrate a minimum level of neuroanatomy.
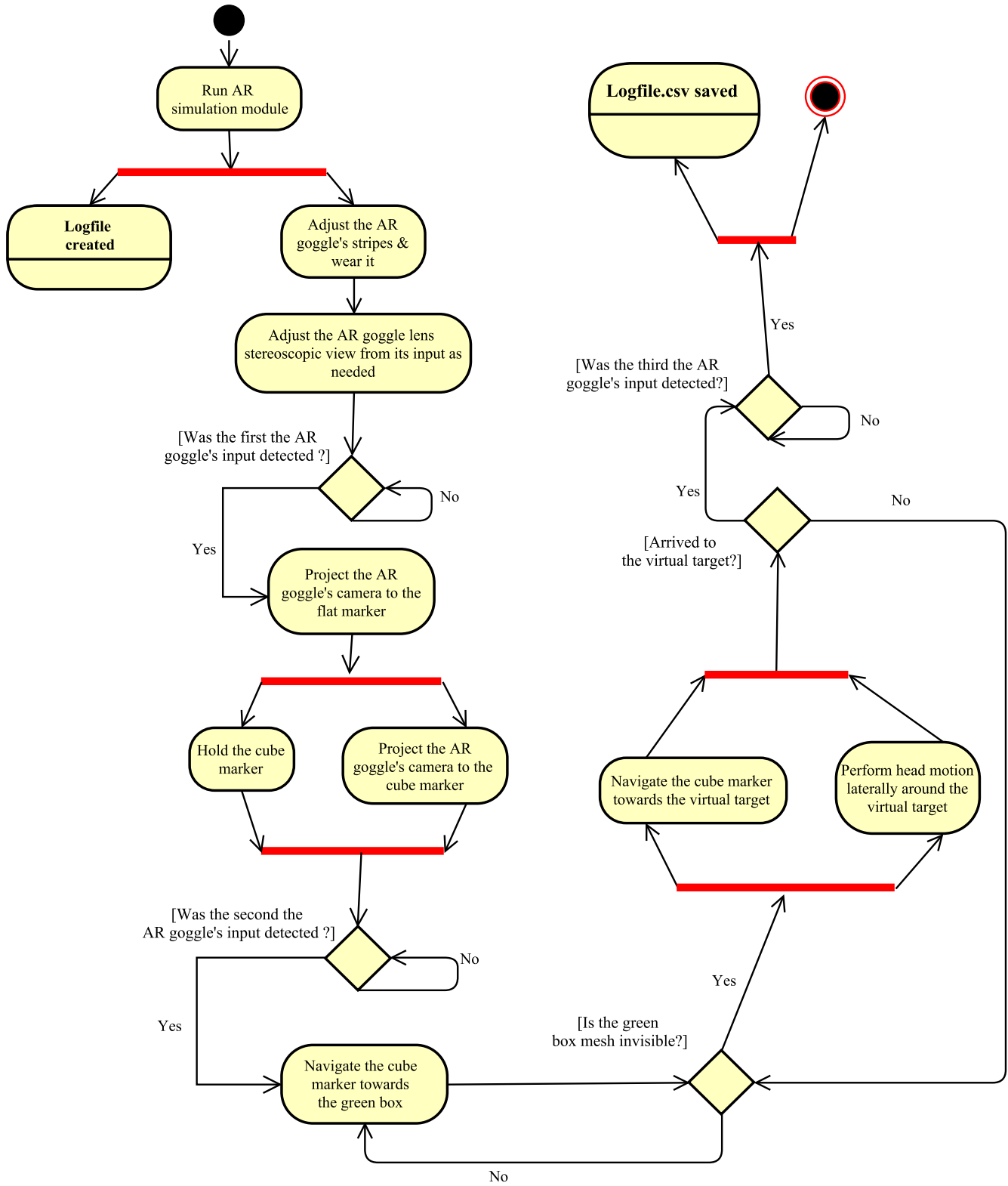
Fig. 5.4: Workflow of EVD placement targeting tasks using the AR simulation module in the second setting. Users will be able to move their hand and hand during the targeting tasks.

5.3.4 Results

Table 5.7 and Table 5.8 depict the outcome of the subjects' trials in terms of the tasks description, and the subjects' hit rate through the first and second settings, respectively. Overall, the data showed that 60% of the subjects were able to achieve the tasks with more than 75% hit rate in the first setting. In the second setting, 80% of the subjects were able to achieve the tasks with more than 75% hit rate. 60% of the subjects spent more time (i.e., more accuracy) in the second setting than the first setting, while 40% spent less time (i.e., less accuracy) in the second setting than the first setting.

Tab. 5.7: Mean and stand deviation values of subjects' tasks and its description throughout the User Study 02 in the first setting.

User ID	Trial counter	A (cm)	W (cm)	ID (bits)	MT (seconds)	IP (bits/ seconds)	Hit rate (%)
User01	8	8 ± 3.3	0.37 ± 0.21	4.3 ± 2	19 ± 12	0.23 ± 0.14	87.5
User02	8	9 ± 0.78	0.37 ± 0.21	4.9 ± 0.95	5.8 ± 3	1 ± 0.42	100
User03	8	4.5 ± 4.9	0.37 ± 0.21	2.3 ± 2.5	4.9 ± 5.5	0.25 ± 0.29	50
User04	8	5.8 ± 4.8	0.37 ± 0.21	2.7 ± 2.3	4.9 ± 6.6	0.5 ± 0.51	62.5
User05	8	6.7 ± 4.2	0.37 ± 0.21	3.7 ± 2.5	10 ± 9.1	0.33 ± 0.28	75
User07	8	6.6 ± 4.1	0.37 ± 0.21	3.8 ± 2.5	8.3 ± 6.7	0.52 ± 0.7	75
User08	8	7.8 ± 3.3	0.37 ± 0.21	4.3 ± 2	14 ± 9.5	0.34 ± 0.22	87.5
User10	8	5.5 ± 4.6	0.37 ± 0.21	3 ± 2.6	6.4 ± 6.2	0.35 ± 0.38	62.5
User12	8	7.8 ± 3.3	0.37 ± 0.21	4.3 ± 2	5.2 ± 2.9	0.85 ± 0.55	87.5
Senior User01	8	3.3 ± 4.6	0.37 ± 0.21	1.8 ± 2.6	3.3 ± 5.2	0.23 ± 0.33	37.5

Tab. 5.8: Mean and stand deviation values of subjects' tasks and its description throughout the User Study 02 in the second setting.

User ID	Trial counter	A (cm)	W (cm)	ID (bits)	MT (seconds)	IP (bits/ seconds)	Hit rate (%)
User01	8	9 ± 0.78	0.37 ± 0.21	4.9 ± 0.95	18 ± 6.8	0.33 ± 0.25	100
User02	8	9.1 ± 0.84	0.38 ± 0.21	4.9 ± 0.96	6.6 ± 1.1	0.76 ± 0.15	100
User03	8	6.7 ± 4.2	0.37 ± 0.21	3.5 ± 2.3	7.3 ± 6.9	0.45 ± 0.38	75
User04	8	6.7 ± 4.2	0.37 ± 0.21	3.6 ± 2.4	5.5 ± 3.6	0.51 ± 0.37	75
User05	8	7.8 ± 3.2	0.37 ± 0.21	4.4 ± 2	9.5 ± 6.2	0.48 ± 0.3	88
User07	8	9 ± 0.78	0.37 ± 0.21	4.9 ± 0.95	12 ± 4.3	0.45 ± 0.19	100
User08	8	5.5 ± 4.6	0.37 ± 0.21	2.8 ± 2.4	5.7 ± 5.4	0.34 ± 0.33	63
User10	8	6.7 ± 4.2	0.37 ± 0.21	3.6 ± 2.4	10 ± 9.1	0.38 ± 0.43	75
User12	8	5.4 ± 4.5	0.31 ± 0.24	3 ± 2.7	4.9 ± 4.5	0.44 ± 0.46	63
Senior User01	8	7 ± 4.3	0.37 ± 0.21	3.5 ± 2.2	5.7 ± 5.7	0.57 ± 0.45	75

5.4   Discussion

The current version of AR simulation module allowed subjects to complete the majority of the targeting task in the first study (i.e., 98.4 %). We believe our design offers a better experience to novices whenever we compared our work to related work developed by Armstrong [15]. In Armstrong [15], novices were able to achieve a hit rate with 59% of the targeting tasks due to narrow range of targeting tasks, AR tracking issues, and light discrepancies.

We noticed that the senior user in the User Study 02 had low hit rate than other novices. We were not expecting that the majority of the novices outperform the senior user in anatomical targeting tasks. Presumably, novices had higher spatial abilities than the senior user, and anatomical knowledge was not a contributing factor to improve the

hit rate. This phenomenon needs more investigation[2].

Within the user studies, there could be two potential threats to its validity. For example, threats to validity might include selection bias towards the participants. In order to recruit participants, we sent mass emails to public email groups without incentives to participation. Another threat to the studies validity is user fatigue during conducting the AR targeting tasks. Eyes or motion sickness, common challenges during AR research, might occur as a result of long exposure to immersive view mode with low lights. The AR goggle headset's weight might be a contributing factor towards user fatigue. However, we did not notice any fatigue signs from the participants, and it is possible that break sessions were granted whenever requested, where participants completed the whole targeting tasks less than 30 minutes, including the training time on the AR simulation modules. The AR goggle headset was made from very light foam-alike materials, and we have not noticed any complaint from the subjects about it (refer to Table 4.2 for more information about the AR goggle headset).

5.5   Summary and Conclusions

In this chapter, we examined our executable for verification purposes to measure the performance of novice users during their EVD targeting tasks between two different user studies. Within the two user studies, the data showed that novices had a learning curve. The subjects' performance and related metrics were reported between the two settings in

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2. Spatial tests would be used to determine the subjects' spatial abilities, such as Mental Rotation Test (MRT) [73]. The subjects will be asked to participate in a locally developed MRT, which is presented in Appendix B.

each study. The next stage of this research is to investigate the novices' depth perception

and its enhancement during their EVD targeting tasks within different settings.

Chapter 6

Investigation of Users' Depth Perception Based on Structure Through Motion Visual Cue

6.1 Introduction

Dey et al. [74] defined human perception as an invisible mental state that should be deduced from the quantitative physical reactions, resulting from human depth judgments. There are two types of depth judgments: egocentric and exocentric. The former is concerned with the distance to an object perceived from the observer's viewpoint, and the latter is concerned with the distance between two objects in the view [74].

- This work has been published as:

  - H. Ghandorh, S. De Ribaupierre, R. Eagleson, "An Investigation on Head Motion and Perceptual Motion Cues Influence on User' Depth Perception for Augmented Reality Neurosurgical Simulators", *the 25th IEEE Conference on Virtual Reality and 3D User Interfaces*, March 18-22, 2018, Reutlingen, Germany.

Currently, depth perception has been reported in terms of depth cues. Reichelt et al. [75] classified depth cues in the human visual perception into oculomotor cues (accommodation, convergence, myosis) and visual cues (binocular, monocular). Furmanski et al. [76] classified depth cues into depth-dependent perceptual cues (transparency, occlusion, size-scaling gradients & texture, shading gradients), perceptual motion (motion parallax, structure-from-motion (SFM)), and binocular cues.

Depth perception has been considered a challenge due to the fact that humans tend to perceive depth motion of an object as primary as a perceptual experience as the perception of its static flatness [71].

Inaccurate user depth perception results into distance underestimation. Accurate distance estimation requires the sequential completion of three mental processes: perceiving, analyzing, and reporting [72]. Distance underestimation can result from a variety of reasons, including the quality of computer graphics, stereoscopic condition, or experience in virtual reality [72]. Lin and Woldegiorgis [72] stated that humans are 94% accurate to distance estimation in the real world, while only 80% accurate to distance estimation in VR or AR spaces. With this in mind, the current design of AR system has become obsolete.

Human beings are capable of perceiving three-dimensional shapes of an object using perceptual motion cues. Treue et al. [77] stated that perceptual human capability towards identifying 3D object depth would improve whenever a motion of the object's parts become apparent. This phenomenon is known as SFM, or kinetic depth effect. By the use of SFM cue, viewers will be able to tie visible features of a moving object and underlying structures to gain a sense of its own geometry, even when the object is

apparent in static displays [76]. Other depth-dependent perceptual cues would enhance the perceptual human capability, for instance, transparency, or shadow) [78]. Few studies concluded that motion cues may aid in depth perception with properly defined geometries and metrically-accurate models [76].

A few studies have investigated how depth perception operates in AR systems [79][78][80], however, they did not focus on HMD-based AR neurosurgical planning aids systems nor use used thoroughly objective assessment of users performance. Sielhorst et al. [79] proposed a new visualization technique for performing spatial tasks in AR space for spine surgery training. The authors investigated the use of a seven different visualization\renderings modes, intended to measuring surgeons' depth perception, and they utilized stereoscopic video see-through HMD-based system worn by surgeons. The authors concluded that a specific kind of visualization is important to increase effectiveness with the AR interaction. Kersten-Oertel et al. [78] conducted user studies about novice and senior neurosurgeons and their response towards depth perception of anatomical knowledge. The authors investigated the use of a variety of different perceptual cues (fog, pseudo-chromadepth, kinetic depth, and depicting edges) based on 2D display and 3D vision glasses. The authors concluded that there is a potential to improve users depth perception based on their techniques. Choi et al. [80] investigated the effect of VR\AR switchable surgical navigation system with distance estimation. The authors conducted multiple user studies based on only AR mode, seamless switching between VR\AR, and VR\AR with minimum distance display, and concluded that minimum distance display contributed to lessening AR limitations in term of depth perception.

Accordingly, this chapter fulfills the third aim of our research study, and it describes

our investigation into whether head motion and perceptual motion cues have any influence on users' depth perception based on the conducted user studies (refer to Section 5.2 and Section 5.3). We hypothesized that head motion and perceptual motion cues will positively influence user performance during conducting targeting tasks in AR space.

6.2 Methodology

We are investigating whether the head motion and perceptual motion cues have any influence on users depth perception throughout both user studies (refer to Section 5.2 and Section 5.3). Before navigating to the rendered target and an accurately hit its center, the subjects moved their head around laterally around the target.

6.3 Results

Figure 6.1 and figure 6.2 portray subjects' performance as a trade-off between speed and accuracy from User Study 01 and User Study 02, respectively. Subjects in the first user study performed the designed set of trials with slow and accurate targeting throughout the first and second settings towards the Very-Slow-Very-Accurate zone (refer to section 4.3.6). Subjects in the second user study performed the designed set of trials with fast and inaccurate targeting throughout the first and second settings towards the Slow-Not-Accurate zone. In both user studies, users' performance trends are represented under hyperbolas curves. The first study found that users' performance trend had a positive shift towards the Very-Fast-Very-Accurate zone, while the second study demonstrated
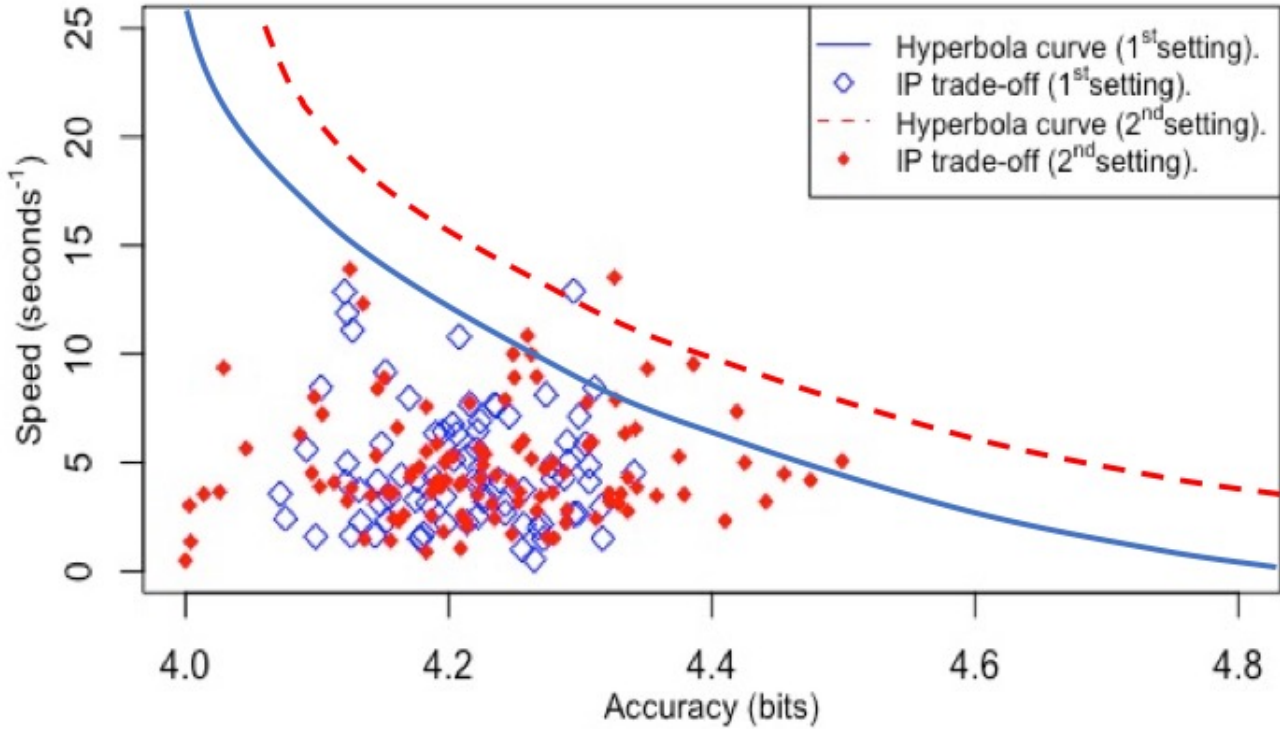
Fig. 6.1: Users' performance trade-off through the User Study 01 with targeting the virtual ellipsoids.

that no significant shifts in the users' performance trend throughout the two settings. Across all settings in the first and second use study, the best performance was in the condition of targeting ellipsoids while using head motions to resolve position in depth.

For each comparison between the two settings, sample data were examined for normality using the Shapiro-Wilk normality test to examine the goodness of fit to a normal distribution. Whenever samples did not fit a normal distribution, the Mann Whitney U test was applied to examine statistical significance. In User Study 01, the data did not show any statistical significance in subjects' performance (p-value = 0.16), DE (p-value = 0.01), or RE (p-value = 0.79) between the two settings. However, the data showed there is a statistical significance of users' TE throughout the two settings
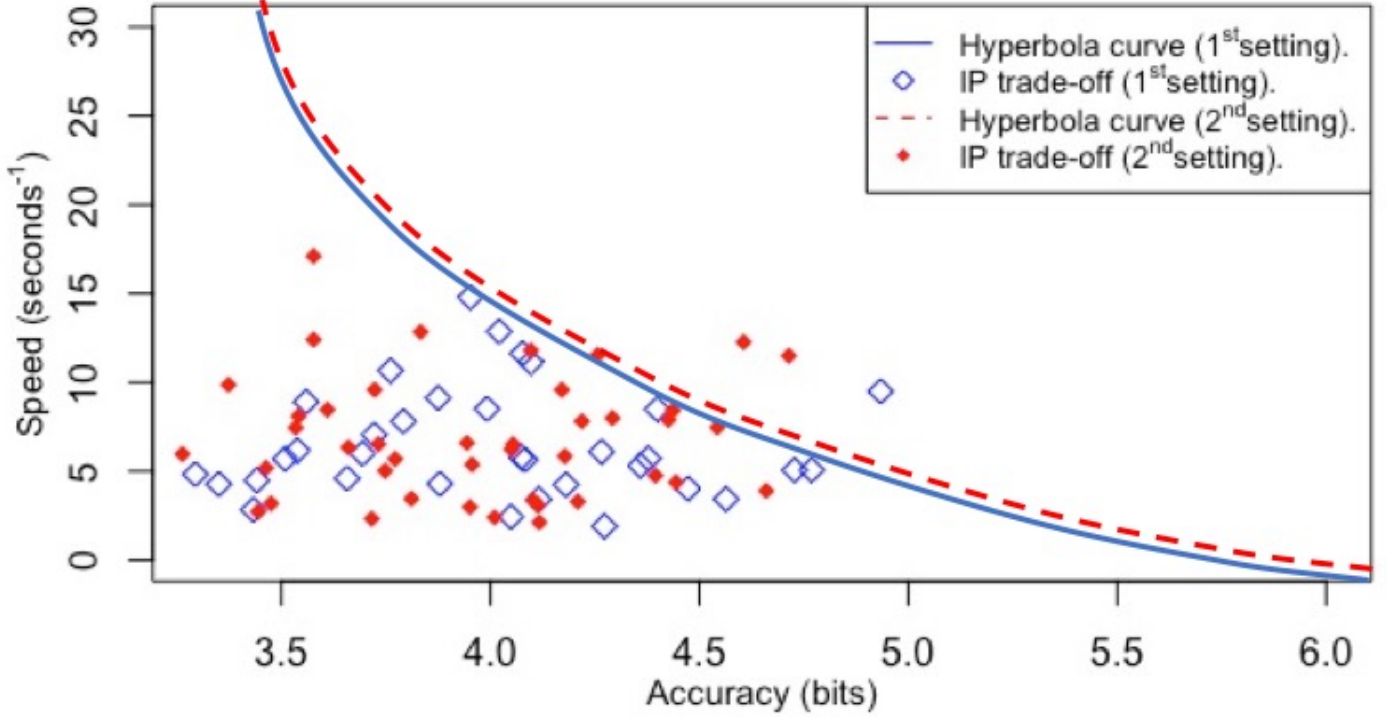
Fig. 6.2: Users' performance trade-off through the User Study 02 with targeting the virtual brain structures.

(p-value $= 6.5\mathrm{e}{-5}$). In User Study 02, the data did not show any significance of users performance (p-value $= 0.93$), or DE (p-value $= 0.45$) between the two settings.

A multiple linear regression model was conducted to examine the influence of DR, TE, and RE upon IP variables throughout the two studies. The overall p-value of the multiple linear regression is 0.0591 (p-value ≥ 0.05) in User Study 01. In User Study 02, the overall p-value of the multiple linear regression is $5.8\mathrm{e}{-14}$ (p-value ≤ 0.05). The data showed that there is a correlation between IP and DE (p-value $= 5.8\mathrm{e}{-11}$) variables in the User Study 02 in the both settings. Moreover, another multiple linear regression model was conducted to examine the influence of HRt upon IP variables between two studies. The overall p-value of the multiple linear regression is 0.0129 (p-value ≤ 0.05),

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indicating that there is a correlation between *IP* and *HRt* variables in both studies.

6.4 Discussion

The data showed that while performing the targeting tasks into ellipsoids meshes was better with head motion; the data showed no improvement when targeting into the brain structures meshes. Presumably, better targeting into ellipsoids meshes phenomenon occurs due to the fact that the tasks were very well-posed for novices. In the other hand, performing the targeting tasks into brain structures meshes required surgical domain knowledge when targeting anatomical structures. As most participants in these studies were not surgical experts, the tasks were difficult due to lack of domain knowledge. Therefore, the perceptual advantage for the head motion was buried when performing the targeting tasks into brain structures meshes.

We offers a better experience to novices whenever we compared our work to related work developed [15]. In [15] novices were able to achieve 59% of the targeting tasks, while our date showed participants had 60% hit rate in the User Study 01 and 80% hit rate in the in the User Study 02. In addition, our results are comparable and consistent with other efforts in terms of user depth direction. We replicated the efforts from [15] that users targeting in depth direction is is worse than desired in the first setting.

Our portable version fits the HMD-based AR modality style. From table 2.1, our generated executable enable participants to experience better hand-eye coordination, extra value of 3D image fusion, implicit 3D interaction, stereoscopic visualization. However, our design did not require extra equipment for record users' physical movement. The

head and hand motion tracking data were collected based on the current integration between Unity and Vuforia APIs. We used image-based markers and virtual camera to infer position and rotation of the subjects through the AR scene. Subjects' tool tracking data were collected from Unity collision detection APIs, and subjects' head motion tracking data should be collected from the Android-enabled smartphone\Unity gyroscope sensors.

6.5   Summary and Conclusions

In this chapter, we are reporting the result of our investigation into whether or not head motion and perception motion cues had an influence on users' performance. This investigation considered subjects' head and hand motion as a possible indicator for better performance.

Chapter 7

Conclusion

7.1 Thesis summary

Preventable medical errors have been considered as a significant concern in the clinical settings. It is important that novices not only gain a high-level of surgical mastery but also receive deliberate training for common neurosurgical procedures and underlying tasks. Conventional surgical teaching and training methods have become obsolete due to rapid complicated clinical needs and technological advancements in the simulation field. Surgical simulators have emerged as an adequate candidate to fill the gap for effective means to teach novices and to ensure a safe and free-error training environments.

Chapter 2 and Chapter 3 outlined basic definitions and background utilized to develop our research ideas and an overview of state-of-the-art AR surgical simulation tools for EVD placement training and planning aids were, respectively.

Chapter 4 outlined the development of two novel AR patient-specific simulation modules based on MDE technique, designed for EVD placement tasks. The AR simulation modules intended for novices training and planning aids purposes. The currently developed executables have the potential towards the training of any 3D psych-motor task, including navigation, or torque. The developed executables are based on low-cost

materials with high customization. With this work, we hope AR development and simulation research communities will use our detailed description as foundation for replication for a variety of applications.

Chapter 5 presented an overview of two users studies to investigate the feasibility of the AR simulation modules as objective assessment tool for users' performance for psycho-motor tasks in the virtual space. Through two users studies, the AR simulation module did not only enable evaluators to identify users' performance's strengths and weak points but also to gain more insights about surgical trials patterns and possible ways to optimize the workflow of needed procedures. Thus, the current model of assessment has the potential to be universal for any domain with 3D psychomotor tasks related. We believe the current model should not be limited to medical simulation, and we hope this work will open the gates for AR simulation research.

Chapter 6 discussed the efficacy of head motion and perceptual motion cues and its influence on users' performance and depth perception. This investigation considered subjects' head and hand motion as a possible indicator for better performance.

This research has contributed to the AR engineering field in the following ways:

1. Investigated the feasibility of development of AR simulation modules based on MDE intended for EVD placement task for training and planning aids for novice residents.

2. Investigated the feasibility of the AR simulation modules as training and teaching means and objectively assessed users' performance for psycho-motor tasks in the virtual space.

3. Investigated the efficacy of head motion and perceptual motion cues on users' performance and depth perception during targeting tasks.

7.2   Future work

Throughout the duration of our research work, a number of interesting research questions raised. The following list spotlights on some unexplored research area:

Enhancement AR simulation module with commercial HMD headset

The current development built base on low-value materials (i.e., less then 100$) for EVD placement for the training and planning aids purpose. Although the current wise integration between Unity and Vuforia offers many advantages for AR community, skill transforming to the clinical settings need sophisticated HMD equipment in order to handle complicated technical issues, for instance, dynamic camera calibration or dynamic trajectory planning. Microsoft HoloLens, a HMD fully untethered holographic computer with cutting-edge optics and sensors, are moving forward towards clinical settings. The next step to our work is to upgrade current design and integrate into Microsoft HoloLens headset and its APIs.

Development of AR simulation tools with playback capabilities

Besides users' hit rate, performance, and accuracy's metrics, the current implementation of the apparatus allowed for collecting and recording run-time tracking data for many

components, for instance, subjects' movements, paths and collision detection towards the targets, within the AR scene. As a result, the current implementation has the potential for a live playback module for guidance purposes. Run-time tracking data could be recorded and transformed to a semi-transparent overlay on training work-spaces as guidance aids for novices and senior neurosurgeons. This feature will be invaluable for teaching novel and complicated surgical tasks, where recorded senior neurosurgeons trials could be played back on real patients during the surgery. Also, the run-time tracking data will act as comprehensive log files generated to notifying the evaluators about how subjects did a certain task. The comprehensive log files could serve as a benchmark for world-scale surgical-driven data centers, by which further computing research could be conducted within the fields of machine learning and medical informatics, for instance.

Development of Neurosurgeon-specific AR simulation tools

Many of the related work for surgical teaching and training applications have focused on the development of surgery-specific tasks with a particular surgical discipline. Few studies, like ours, have paid more attention to the development of patient- and scenario-specific. For future designs, fully customization neurosurgeon-specific AR simulation tools could emerge. Such tools could act as a personal assistant and guide for a variety of surgery stages, for instance, postoperative.

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Appendix A

Appendix A : Research Ethics Approvals

Our conducted research involved human subjects. The following approvals state the needed ethics approvals for our studies.

LAWSON FINAL APPROVAL NOTICE

RESEARCH OFFICE REVIEW NO.: R-12-465

PROJECT TITLE: Learning with virtual environments

PRINCIPAL INVESTIGATOR: Dr. Sandrine de Ribaupierre

LAWSON APPROVAL DATE: December 20, 2012

Health Sciences REB#: 102917

Please be advised that the above project was reviewed by the Clinical Research Impact Committee and the project:

Was Approved

PLEASE INFORM THE APPROPRIATE NURSING UNITS, LABORATORIES, ETC. BEFORE STARTING THIS PROTOCOL. THE RESEARCH OFFICE NUMBER MUST BE USED WHEN COMMUNICATING WITH THESE AREAS.

Dr. David Hill
V.P. Research
Lawson Health Research Institute

All future correspondence concerning this study should include the Research Office Review Number and should be directed to Sherry Paiva, CRIC Liaison, Lawson Health Research Institute, 750 Baseline Road, East, Suite 300.

cc: Administration

Fig. A.1: A copy of research ethics approval titled "Learning with virtual environments."

Western Research

Western University Non-Medical Research Ethics Board
NMREB Amendment Approval Notice

Principal Investigator: Dr. Sandrine de Ribaupierre
Department & Institution: Schulich School of Medicine and Dentistry\Clinical Neurological Sciences, Western University

NMREB File Number: 102917
Study Title: Learning with virtual environments

NMREB Revision Approval Date: November 21, 2016
NMREB Expiry Date: December 12, 2017

Documents Approved and/or Received for Information:

Document Name	Comments	Version Date
Revised Western University Protocol	Received Nov 17, 2016	

The Western University Non-Medical Science Research Ethics Board (NMREB) has reviewed and approved the amendment to the above named study, as of the NMREB Amendment Approval Date noted above.

NMREB approval for this study remains valid until the NMREB Expiry Date noted above, conditional to timely submission and acceptance of NMREB Continuing Ethics Review.

The Western University NMREB operates in compliance with the Tri-Council Policy Statement Ethical Conduct for Research Involving Humans (TCPS2), the Ontario Personal Health Information Protection Act (PHIPA, 2004), and the applicable laws and regulations of Ontario.

Members of the NMREB who are named as Investigators in research studies do not participate in discussions related to, nor vote on such studies when they are presented to the REB.

The NMREB is registered with the U.S. Department of Health & Human Services under the IRB registration number IRB 00000941

Ethics Officer, on behalf of Dr. Riley Hinson, NMREB Chair

Ethics Officer: Erika Basile ___ Katelyn Harris ___ Nicole Kaniki ___ Grace Kelly ___ Vikki Tran ___ Karen Gopaul ___

Fig. A.2: A copy of research ethics amendment titled "Learning with virtual environments."

Research Ethics

Western University Health Science Research Ethics Board
HSREB Amendment Approval Notice

Principal Investigator: Dr. Sandrine de Ribaupierre
Department & Institution: Schulich School of Medicine and Dentistry\Clinical Neurological Sciences,Western University

HSREB File Number: 102917
Study Title: Learning with virtual environments
Sponsor:

HSREB Amendment Approval Date: June 23, 2014
HSREB Expiry Date: August 31, 2017

Documents Approved and/or Received for Information:

Document Name	Comments	Version Date
Change in Study Personnel	Adding co-investigators as more students are working on parts of the study - Lauren Allen - PhD candidate - lallen22@uwo.ca - Ryan Armstrong - PhD candidate - rarmst2@uwo.ca - Dayna Noltie - medical student -	

The Western University Health Science Research Ethics Board (HSREB) has reviewed and approved the amendment to the above named study, as of the HSREB Initial Approval Date noted above.

HSREB approval for this study remains valid until the HSREB Expiry Date noted above, conditional to timely submission and acceptance of HSREB Continuing Ethics Review. If an Updated Approval Notice is required prior to the HSREB Expiry Date, the Principal Investigator is responsible for completing and submitting an HSREB Updated Approval Form in a timely fashion.

The Western University HSREB operates in compliance with the Tri-Council Policy Statement Ethical Conduct for Research Involving Humans (TCPS2), the International Conference on Harmonization of Technical Requirements for Registration of Pharmaceuticals for Human Use Guideline for Good Clinical Practice Practices (ICH E6 R1), the Ontario Personal Health Information Protection Act (PHIPA, 2004), Part 4 of the Natural Health Product Regulations, Health Canada Medical Device Regulations and Part C, Division 5, of the Food and Drug Regulations of Health Canada.

Members of the HSREB who are named as Investigators in research studies do not participate in discussions related to, nor vote on such studies when they are presented to the REB.

The HSREB is registered with the U.S. Department of Health & Human Services under the IRB registration number IRB 00000940.

Ethics Officer to Contact for Further Information

Erika Basile	Grace Kelly	Mina Mekhail	Vikki Tran
ebasile@uwo.ca	grace.kelly@uwo.ca	mmekhail@uwo.ca	vikki.tran@uwo.ca

This is an official document. Please retain the original in your files.

Fig. A.3: A copy of research ethics amendment titled "Learning with virtual environments."

Appendix B

Appendix B : Mental Rotation Test

The MRT was built upon a highly customizable Qualtrics platform (Seattle, Washington, United States). It built to investigate whether spatial abilities have any impact on users' performance.

Western
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Mental Rotation Test

Introduction

.
Participants in this study will be asked to complete the following items: a) demographic survey and b) spatial ability test. The spatial ability test (i.e., **Mental Rotation Test (MRT)1**) is used to examine users' ability to mentally rotate a visual representation of a two-dimensional object based on to their visual-spatial skills. The purpose of the test is to assess users' visual-spatial abilities, the last part of the experimental Augmented reality user study.

The test contains 25 blocks with 25 questions, where each block includes one question. Each block consists of two parts: 1) the question section with five shapes (i.e., original figure in the top part, and four possible answer figures in the bottom part) and 2) the answer section with four multiple-choice answers. **When the participants perform the test, they will pick the shape that is identical to the original figure.** Sometimes, it is possible that there is more than one correct answer that matches the original figure. The test should not take more than 10 minutes.

In order to perform the test, please follow the below procedure :

1- In each block\question, check out the original figure at the top part and try to maintain a mental image of it from different directions.
2- Rotate the figure mentally until a comparison can be made.
3- Make the comparison with the other four figures in the bottom part.
4- **Choose only one answer which is identical to the original figure in the answer section.**
5- Press (>>) button to go to the next question.

To start, please press the starting button (>>).

Thanks for participation.

_____
1 This test is composed of the figures provided by Shepard and Metzler (1978) 2, and is, essentially, an Autocad-redrawn version of the Vandenberg & Kuse MRT test 3.
2 Shepard, R. and Metzler, J. (1971). Mental Rotation of Three-Dimensional Objects. Science, 171(3972), pp.701-703.
3 Peters, M., Laeng, B., Latham, K., Jackson, M., Zaiyouna, R., & Richardson, C. (1995). A redrawn Vandenberg and Kuse Mental Rotations Test: Different versions and factors that affect performance. Brain and Cognition, 28(1), 39-58.

Demographics

D1. Please type your email

[   ]

D2. How old are you?

○ **20-29**

○ **30-39**

○ **40-49**

○ **Above 50**

D3. What is your gender?

○ **Male**

○ **Female**

D4. What is your background?

○ **Medical**

○ **Engineering**

○ **Anatomy**

○ **Other? Please type it here :**

[   ]

Rotation mental test

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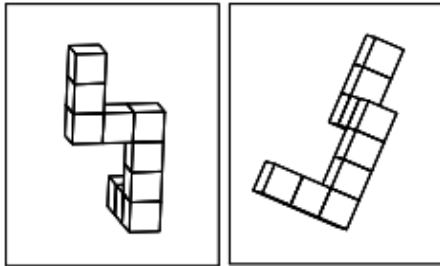**Page Submit:** *0 seconds*

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0 0 0 0 0 0
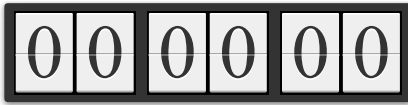
Q1. **Which image is the same as the Figure 1 ?**
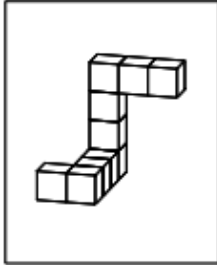
Figure 1
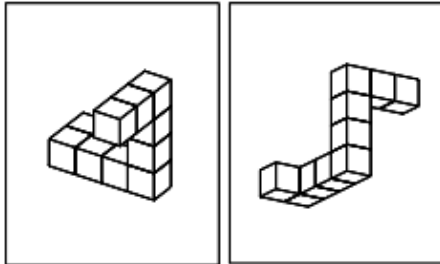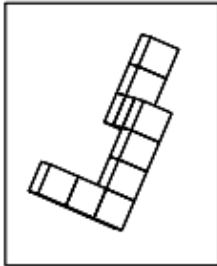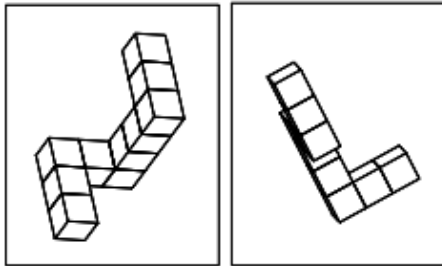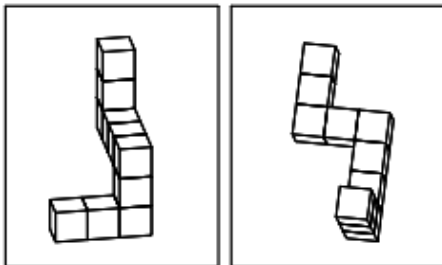

A   B
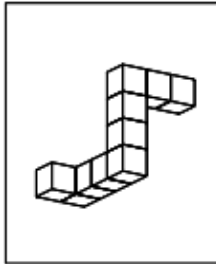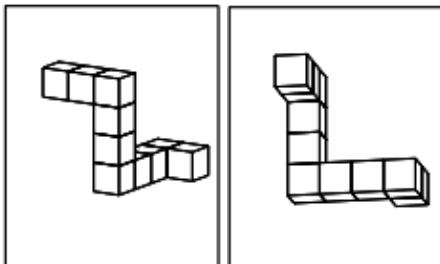
C   D
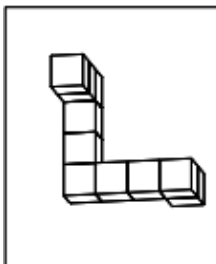
○ A

○ B

○ C

○ D

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Q2. **Which image is the same as the Figure 2 ?**

Figure 2
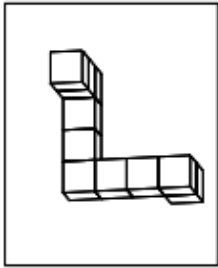
A
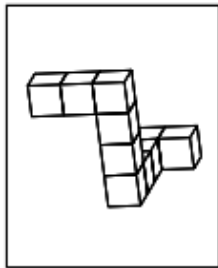
B
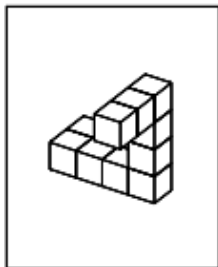
C
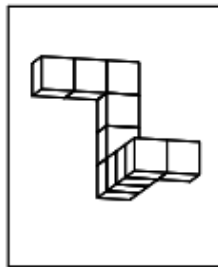
D

○ **D**

○ **B**

○ **C**

○ **A**

Q3. **Which image is the same as the Figure 3 ?**

Figure 3
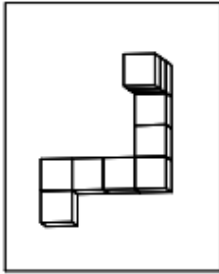
A
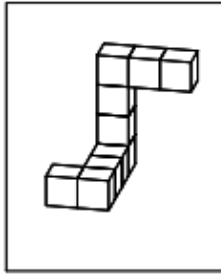
B
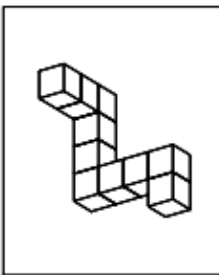
C
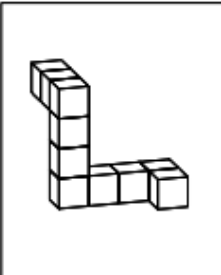
D

○ **C**

○ **B**

○ **A**

○ **D**

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Q4. **Which image is the same as the Figure 4 ?**
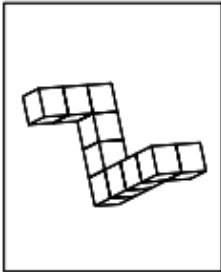
Figure 4
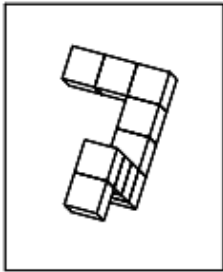
A
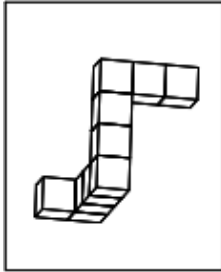
B
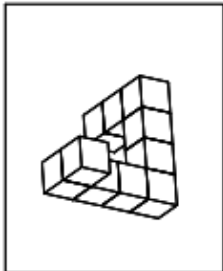
C
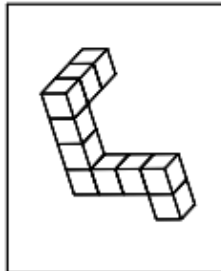
D

○ **D**

○ **C**

○ **B**

○ **A**

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Q5. **Which image is the same as the Figure 5 ?**

Figure 5
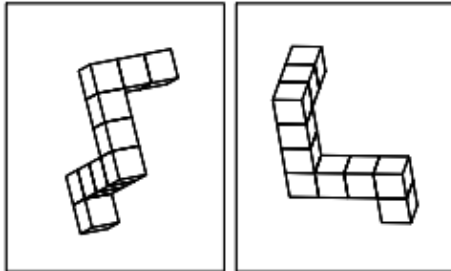
A

B
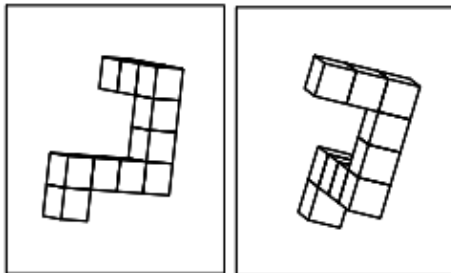
C

D

○ **A**

○ **B**

○ **C**

○ **D**

Q6. **Which image is the same as the Figure 6 ?**

Figure 6
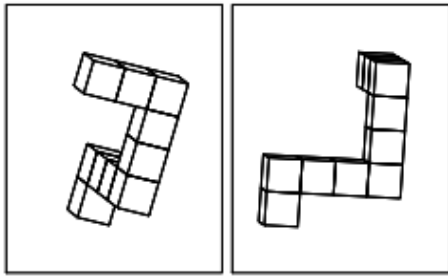
A

B
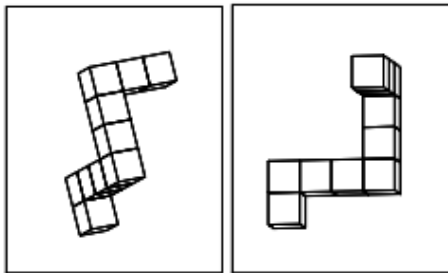
C

D

○ **B**

○ **D**

○ **C**

○ **A**

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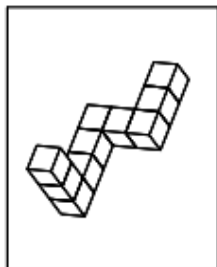

Q7. **Which image is the same as the Figure 7 ?**
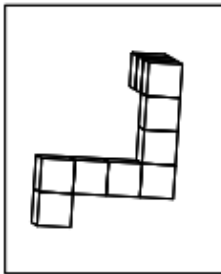
Figure 7
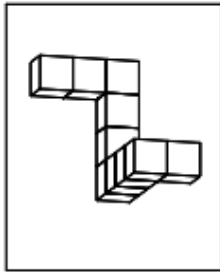
A   **B**
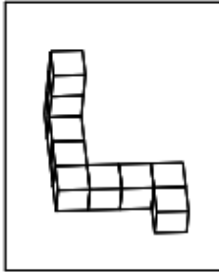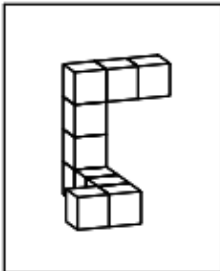
C   **D**
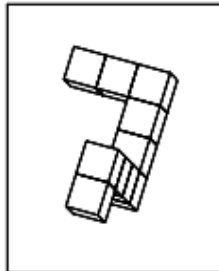
○ **A**

○ **B**

○ **C**

○ **D**

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Q8. **Which image is the same as the Figure 8 ?**

Figure 8
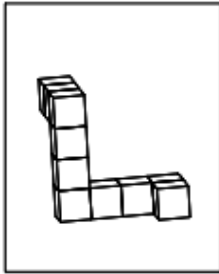
A
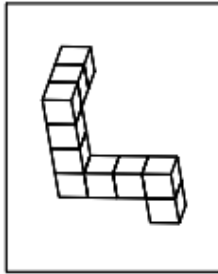
B
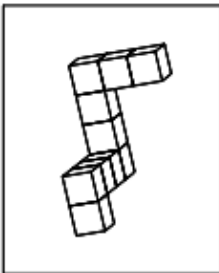
C
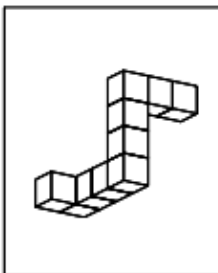
D

○ **C**

○ **B**

○ **D**

○ **A**

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Q9. **Which image is the same as the Figure 9 ?**
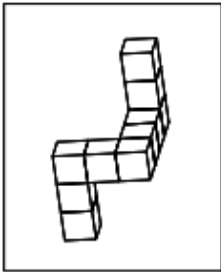
Figure 9
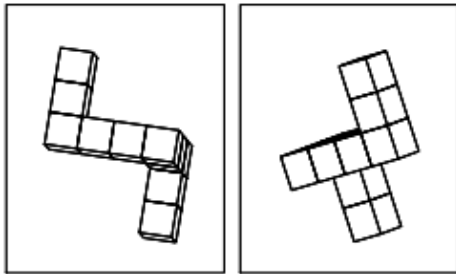
A   **B**
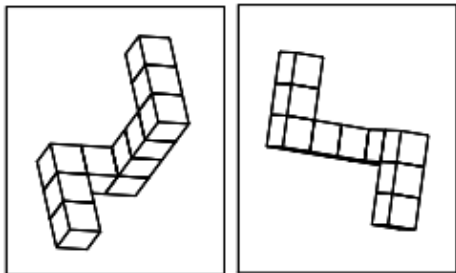
C   **D**

○ **A**

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Q10. **Which image is the same as the Figure 10 ?**

Figure 10
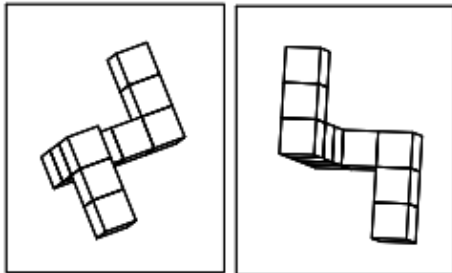
A

B
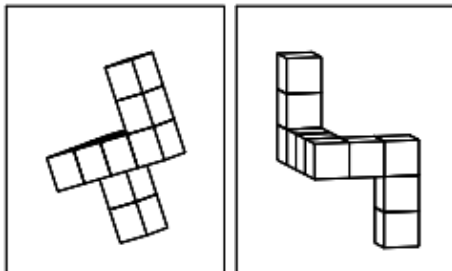
C

D

○ **B**

○ **A**

○ **D**

○ **C**

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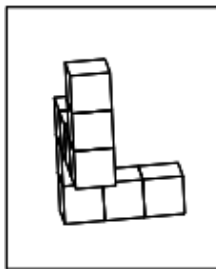

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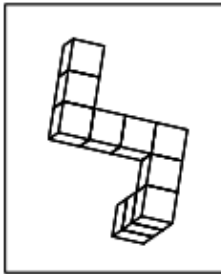
Figure 11
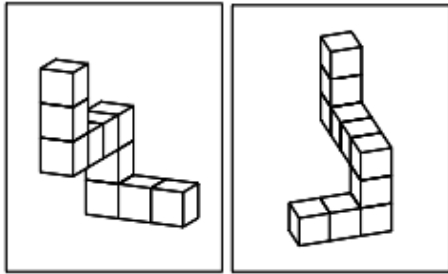
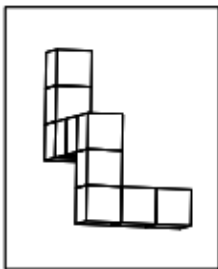**A**   **B**
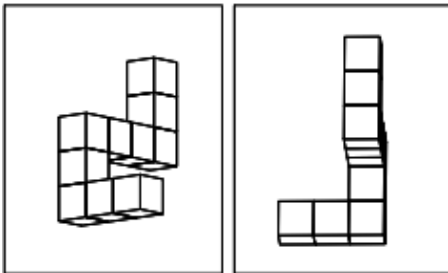
C   **D**

○ **C**

○ **A**

○ **B**

○ **D**

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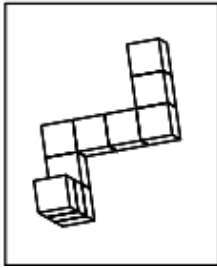

Q12. **Which image is the same as the Figure 12 ?**
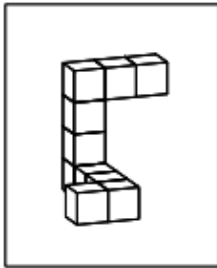
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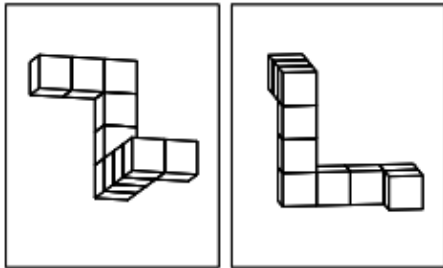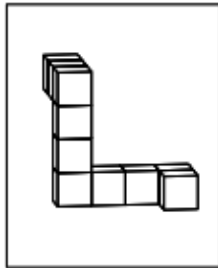
   A   **B**
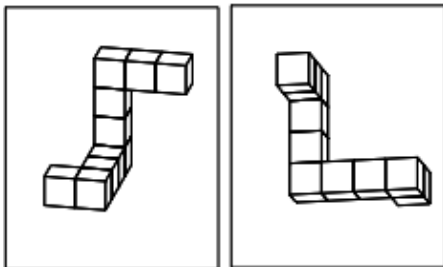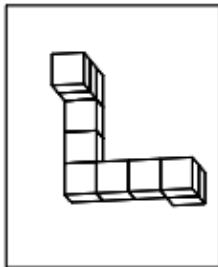
   C   **D**

○ **D**

○ **C**

○ **A**

○ **B**

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Q13. **Which image is the same as the Figure 13 ?**
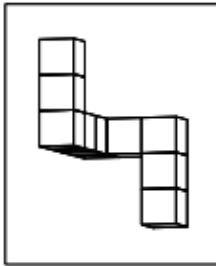
Figure 13
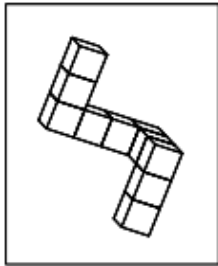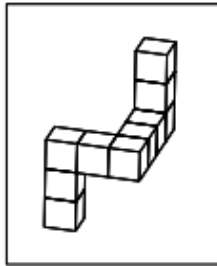
A   **B**
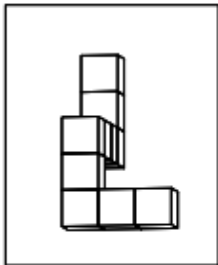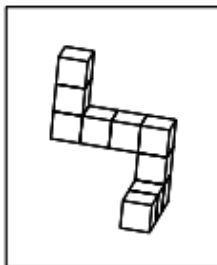
C   **D**

○ **A**

○ **B**

○ **D**

○ **C**

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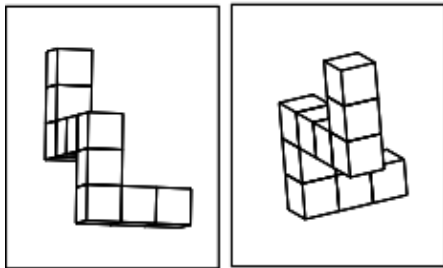**Click Count:** *0 clicks*

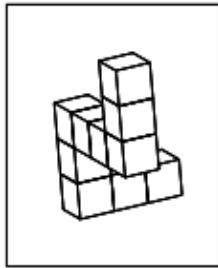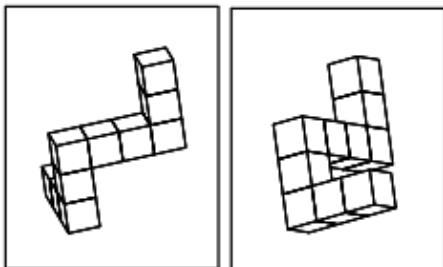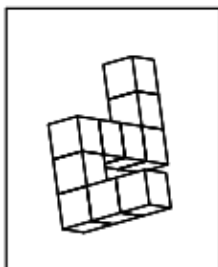

Q14. **Which image is the same as the Figure 14 ?**
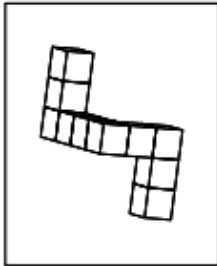
Figure 14
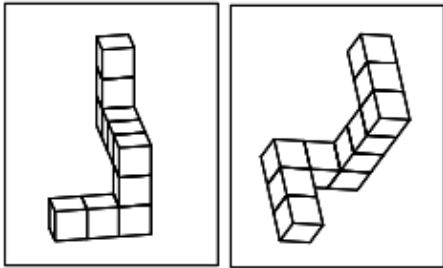
A   B
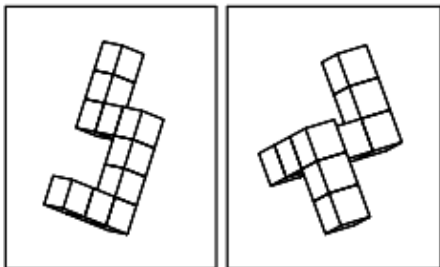
C   D

○ **B**

○ **A**

○ **C**

○ **D**

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Q15. **Which image is the same as the Figure 15 ?**
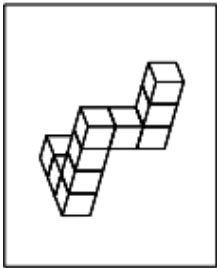
Figure 15
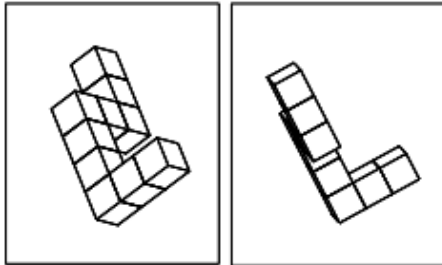
A   B
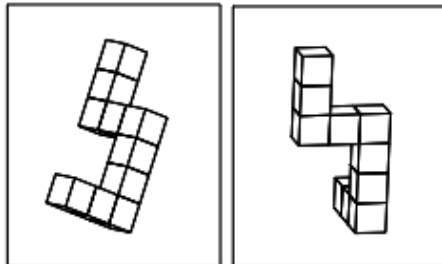
C   D

○ **B**

○ **D**

○ **C**

○ **A**

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Q16. **Which image is the same as the Figure 16 ?**
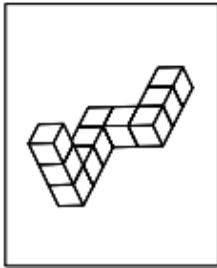
Figure 16

A   **B**
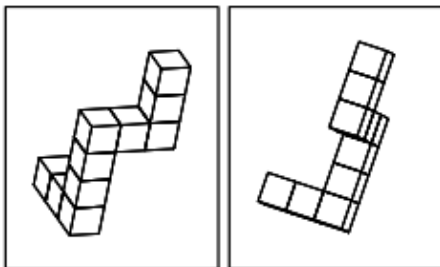
C   **D**

○ **D**

○ **C**

○ **B**

○ **A**

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Q17. **Which image is the same as the Figure 17 ?**

Figure 17

A   **B**
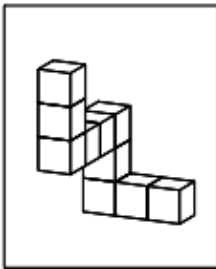

C   **D**

○ **C**

○ **B**

○ **A**

○ **D**

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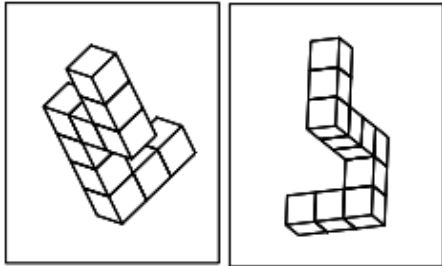
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Q18. **Which image is the same as the Figure 18 ?**
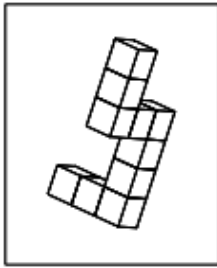
Figure 18
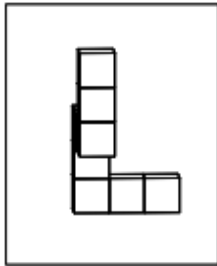
A   B
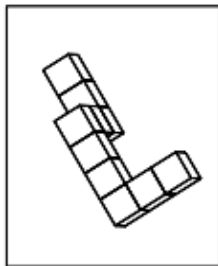
C   D
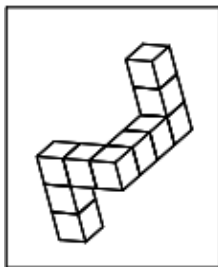
○ **A**

○ **B**

○ **C**

○ **D**

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Q19. **Which image is the same as the Figure 19 ?**

Figure 19

A   **B**

C   **D**

○ **D**

○ **C**

○ **A**

○ **B**

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Q20. **Which image is the same as the Figure 20 ?**

Figure 20

A   **B**

C   **D**

○ **D**

○ **A**

○ **B**

○ **C**

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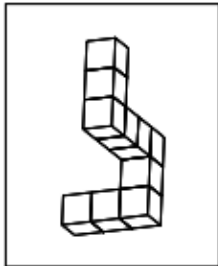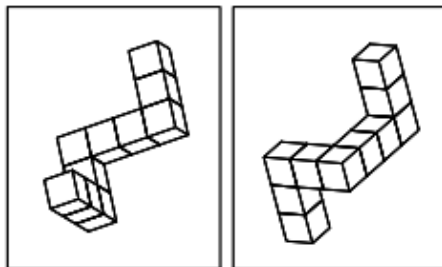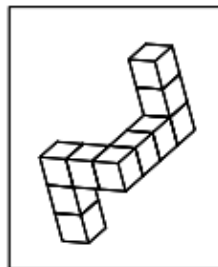
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Q21. **Which image is the same as the Figure 21 ?**
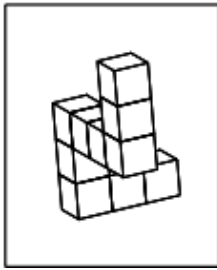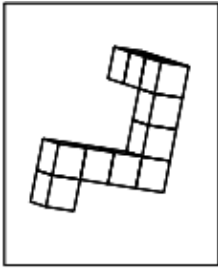

Figure 21
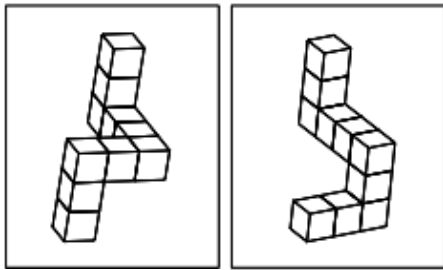
A   B
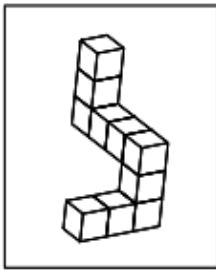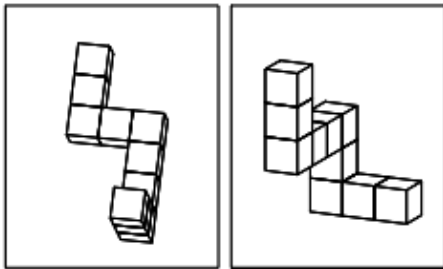
C   D

○ B

○ D

○ C

○ A

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Q22. **Which image is the same as the Figure 22 ?**
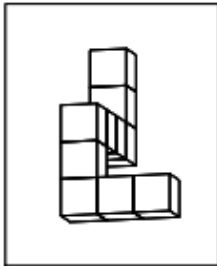
Figure 22

A **B**

C **D**

○ **D**

○ **C**

○ **B**

○ **A**

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Q23. **Which image is the same as the Figure 23 ?**

Figure 23
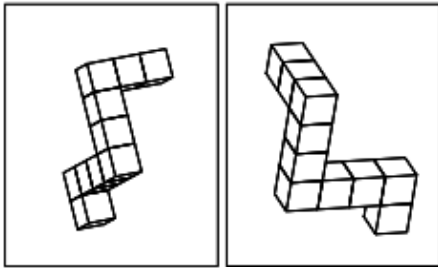
A   **B**
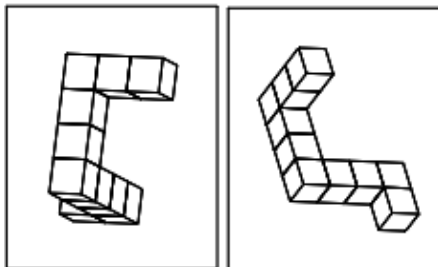
C   **D**

○ **D**

○ **B**

○ **C**

○ **A**

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Q24. **Which image is the same as the Figure 24 ?**
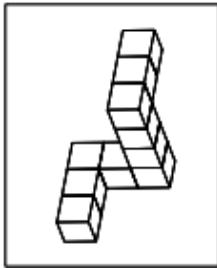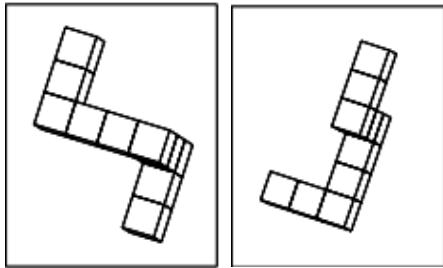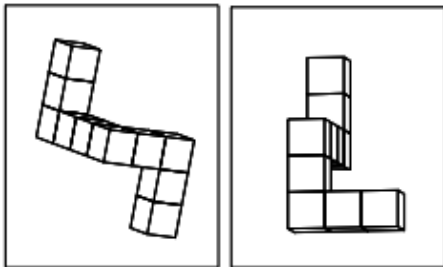

Figure 24

A   B

C   D

○ A

○ B

○ C

○ D

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Q25. **Which image is the same as the Figure 25 ?**
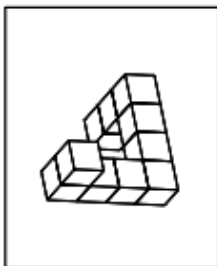
Figure 25

A

B

C

D

○ **B**

○ **A**

○ **C**

○ **D**

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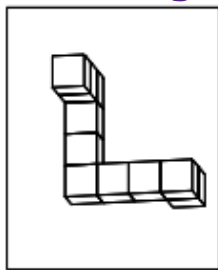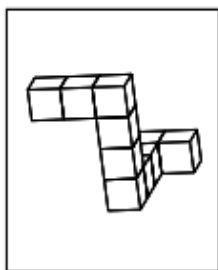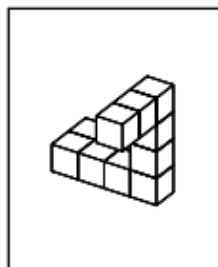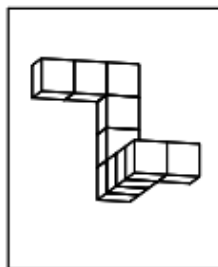
Curriculum Vitae

Name:	**Hamza Waleed Ghandorh**
Year of Birth:	1984

Education:

Ph.D.	Department of Electrical and Computer Engineering
2012 - 2017	Western University, London, Ontario, Canada
Major	Software Engineering
M.Sc.	Department of Computer Science,
2009 - 2011	Western University, London, Ontario, Canada
Major	Computer Science
B.Sc.	Department of Computer Science
2003- 2008	King Abdullaziz University, Jeddah, Saudi Arabia
Major	Computer Science

Experience:

Teaching Assistant	Western University, London, Ontario, Canada
2012 - 2013	Department of Electrical and Computer Engineering
List of courses	ECE 2250: Software Construction - (Fall 2013)
	ECE 4450: Software Engineering Design II - (Fall\Winter 2013)
Guest Lecturer	King Collage, London, On, Canada
March 15	Collage of Computer Science and Engineering
Topic:	Introduction to Big Data
Lecture	Taibah University, Madinah, Saudi Arabia
June 15- Present	Collage of Computer Science and Engineering

Awards:

Fellowship	Taibah University

15 - 17	Saudi Cultural Bureau, Ottawa, Ontario, Canada
	To pursue Doctoral studies at Western University
Fellowship	King Abdullah scholarship program
09 - 14	Saudi Cultural Bureau, Ottawa, Ontario, Canada
	To pursue Masters and Doctoral studies at Western University

List of Publications:

- H. Ghandorh, "Mapping BPEL processes to diagnostic models", *School of Graduate and Postdoctoral Studies, University of Western Ontario*, M.Sc. dissertation, 2011 https://goo.gl/GBR4Kx.

- H. Ghandorh and H. Lutfiyya, "Automated Mapping of Business Process Execution Language to Diagnostics Models", *In Proceedings of the 5th International Conference on Cloud Computing and Services Science*, 2015, pages 251-259.

- H. Ghandorh, L. Capretz, and A. Nassif, "In Need of a Domain-Specific Language Modeling Notation for Smartphone Applications with Portable Capability", *Mobile Web and Intelligent Information Systems*, 2015, pages 218-227.

- H. Ghandorh, S. De Ribaupierre, R. Eagleson, "Development of Augmented Reality Training Simulator Systems for Neurosurgery Using Model-Driven Software Engineering", *IEEE 30th Canadian Conference on Electrical and Computer Engineering (CCECE) [Computer and Software Techniques Track]*, April 2017, Windsor, Ont, Canada.

- H. Ghandorh, S. De Ribaupierre, R. Eagleson, "An Augmented Reality-based Platform for Users' Training and Performance Assessment for Neurosurgical Targeting Tasks", *The 9th annual International Conference on Education and New Learning Technologies*, July 2017, Barcelona, Spain.

- H. Ghandorh, S. De Ribaupierre, R. Eagleson, "An Investigation on Head Motion and Perceptual Motion Cues Influence on User' Depth Perception for Augmented Reality Neurosurgical Simulators", *the 25th IEEE Conference on Virtual Reality and 3D User Interfaces*, March 18-22, 2018, Reutlingen, Germany.

List of Presentations:

- H. Ghandorh, "Mapping BPEL Process to Diagnostics Models," MSc dissertation, Western University, December 2011.

- H. Ghandorh, "Implementation of Employees Performance System Using Fuzzy Logic", In: *IEEE London the Electrical and Computer Engineering Graduate Symposium 2013*, London, On, Canada, July 24—25, 2013.

- H. Ghandorh, "In Need of a Domain Specific Modeling Notation for Smartphone Applications with Portable Capability". In: *IEEE London the Electrical and Computer Engineering Graduate Symposium 2015*, London, On, Canada, May 12-14, 2015.

- H. Ghandorh, "Neurosurgery Planning and Training for Targeting Tasks in Augmented Reality Environment: User Performance Analysis," Poster, London Health Researhc Day 2017, March 2017, London, Ont, Canada.

- H. Ghandorh, "Development of Augmented Reality Training Simulator Systems for Neurosurgery Using Model-Driven Software Engineering", *IEEE 30th Canadian Conference on Electrical and Computer Engineering (CCECE) [Computer and Software Techniques Track]*, April 2017, Windsor, Ont, Canada.